AD-781 762

PRELIMINARY STUDY OF THE CATALYTIC COMBUSTOR CONCEPT AS APPLIED TO AIRCRAFT GAS TURBINES

William S. Blazowski, et al

Air Force Aero Propulsion Laboratory
Wright-Patterson Air Force Base, Ohio

May 1974

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UNCLASSIFIED
Security Classification

AD-718762

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Air Force Aero Propulsion Laboratory (SFF)
Wright-Patterson AFB, Ohio 45433

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
PRELIMINARY STUDY OF THE CATALYTIC COMBUSTOR CONCEPT AS APPLIED TO AIRCRAFT GAS TURBINES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final report January 1972 - February 1974

5. AUTHOR(S) (First name, middle initial, last name)
William S. Blazowski
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6. REPORT DATE
May 1974

7a. TOTAL NO. OF PAGES
65

7b. NO. OF REFS
13

8a. CONTRACT OR GRANT NO.

b. PROJECT NO. 3048

c. Task No. 304805

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
AFAPL-TR-74-32

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Air Force Aero Propulsion Laboratory (SFF)
Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

This investigation was intended to study the feasibility of using solid catalytic beds in the reaction zone of aircraft gas turbine combustors. The catalytic unit was supplied by Engelhard Industries, Menlo Park, New Jersey, and details of the unit not described in this report are considered proprietary. Since the catalytic combustor operates at low-equivalence ratios throughout (there is no near-stoichiometric operation as in most conventional combustors), oxide of nitrogen emissions were forecast to be extremely low. JP-4 fuel was used throughout the experimental test program. Flashback and preignition were observed and the fuel introduction system developed to partially overcome these problems is described. At all operating conditions tested, NO_x concentration was to be below 2 ppmV -- two orders of magnitude below that expected from a conventional combustor operated under similar inlet and exhaust conditions. Virtually 100% combustion efficiency was obtained at combustor inlet temperatures above 700°F and fuel-air ratios above .02. Specific heat release rates of 3.5 X 10^6 $\frac{\text{BTU}}{\text{atm-hr-ft}^3}$ were achieved with high efficiency. Since the measured combustor pressure drop was small ($\Delta P/P < 1\%$), some additional gains in heat release rate might be obtained for additional pressure drop sacrifice. As inlet temperatures and fuel-air ratios decreased or reference velocities increased, efficiency dropped sharply. Since the combustor tested was intended to demonstrate the concept's potential at high temperature operation, results described corresponding to the lower-power conditions do not at all represent what may be optimally achieved. No significant effect of pressure on combustion efficiency was determined over the 4-11 atmosphere range tested.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Pollution						
Combustion						
Catalysis						
Exhaust Emissions						
Gas Turbines						
Nitrogen Oxides						
Combustion Efficiency						

AFAPL-TR-74-32 ABSTRACT

No reduction in performance was noted over the 28 hours of test operation. Improvements based on the information developed in this investigation are likely, and further investigations are recommended.

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AS APPLIED TO AIRCRAFT GAS TURBINES

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FOREWORD

Information presented in this report is the result of an Air Force Aero Propulsion Laboratory (AFAPL) in-house program. Financial support for this program was obtained from the Air Force Control of Noxious Effluents Program monitored by the Air Force Weapons Laboratory, Kirtland AFB, New Mexico. The catalytic unit tested was supplied to AFAPL by Engelhard Industries of Menlo Park, New Jersey, under Contract F33615-72-C-1742. Descriptions and specifications of the unit other than those described in this report are regarded as proprietary to Engelhard Industries. The cooperation and assistance of Engelhard Industries and especially Dr. W. Pfefferle, Dr. R. Carrubba, and P. Flannigan are acknowledged.

The testing was conducted in the Fuels Branch, AFAPL/SFF, Wright-Patterson Air Force Base, Ohio, under project 3048, "Fuels, Lubrication and Fire Protection", Task 304805, "Aero Propulsion Fuels". The work covered the period of January 1972 through February 1974.

The authors wish to express their appreciation to technicians H. Reeves, G. Boggs, W. Borne, T. Campbell and K. Baughman for their exceptional performance in accomplishing this work. Further, we thank foreman P. Waker for facilities coordination and technician supervision during the conduct of this project.

This report was submitted by the authors March 1974.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Arthur V. Churchill

ARTHUR V. CHURCHILL
Chief, Fuels Branch
Fuels and Lubrication Division

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INTRODUCTION

The aircraft has recently been identified (Reference 1)* as a significant source of pollutant emission by the United States Environmental Protection Agency (EPA). This conclusion is based on studies of airports and their surrounding neighborhoods where ground-level aircraft engine emissions of carbon monoxide (CO), unburned hydrocarbons (C_xH_y), and oxides of nitrogen (NO_x)** have been found to be significant. EPA has developed standards for aircraft turbine engines (Reference 2) which will cause the ambient concentrations of CO and photochemical oxidants (the principal objectionable byproduct of C_xH_y and NO_x emissions) in the airfield environment to be reduced to levels approaching Federal ambient air quality standards.

Technology for reduction of smoke emission is now in hand. Engines developed in the past few years have invisible exhaust plumes and the above mentioned EPA standards are intended to insure the same for future engines. Although the exhaust plume visibility problem appears to be solved, investigations of the extent of engine particulate emissions and their environmental effect continue.

An additional possible environmental problem has been associated with aircraft operating in the stratosphere (Reference 3). Chemical

*Numbers in parentheses indicate references listed at end of report
**Emission of nitric and nitrous oxides (NO and NO_2) are collectively expressed as NO_x.

reactions which could deplete the earth's ozone layer are known to be catalyzed by the presence of nitrogen oxides. Because of uncertainities in prediction of stratospheric mixing and chemical processes, the extent of the ozone depletion for given amounts of aircraft NO_x ingestion is not known. A significant ozone depletion would allow increased amounts of ultraviolet radiation to pass through the stratosphere and impinge on the earth's surface causing possible environmental damage and physical harm to humans. Because of the present uncertainities, no standards have been issued for stratospheric NO_x emission by any Federal agency.

Many emission control techniques have been identified. Significant reductions of CO and C_xH_y emissions at idle (where 95% of emissions occur over a typical landing/take-off cycle) have been demonstrated. NO_x emission reductions have also been achieved by hardware modification. Further reduction will require advanced techniques involving fuel-air premixing and prevaporization, staged combustion, and possibly, variable geometry combustors. The NASA Clean Combustor Program (Reference 4) is presently investigating some of these same techniques. Considerable disagreement presently exists regarding the extent to which these techniques will reduce emissions.

Before speculating on these levels here, the parameters of importance must be defined. Emission of CO, C_xH_y and NO_x are expressed in terms of the emission index, gm pollutant/kg fuel. The

relationships between this parameter and commonly-measured quantities are given in Reference 5. The normalization to fuel flow enables a more logical assessment of the combustor's design by eliminating the effects of engine size and configuration. This does not imply, however, that the engine thermodynamic cycle has no effect on the emission index; it may be shown to be strongly related to combustor inlet conditions for both idle CO and C_xH_y emission and for NO_x emission in any operating mode.

At idle the CO and C_xH_y emission indicies can be directly related to combustion efficiency, η

$$\eta = 1 - (2.32 \times 10^{-4}\ EI_{CO} + 10^{-3}\ EI_{C_xH_y}) \qquad (1)$$

where EI_{CO} is the carbon monoxide emission index and $EI_{C_xH_y}$ is the hydrocarbon emission index. If one were to plot the combustion inefficiency $(1-\eta)$ versus combustor inlet temperature, T_3, for a number of engines, a definite trend would be apparent (Figure 1). Technology advancements, which have allowed increases in take-off and cruise pressure ratios to improve power and specific fuel consumption, have also resulted in higher idle values of T_3. CO and C_xH_y emissions from newer engines are inherently lower than older engines because of this trend.

The increased T_3 values of newer engines, however, cause NO_x

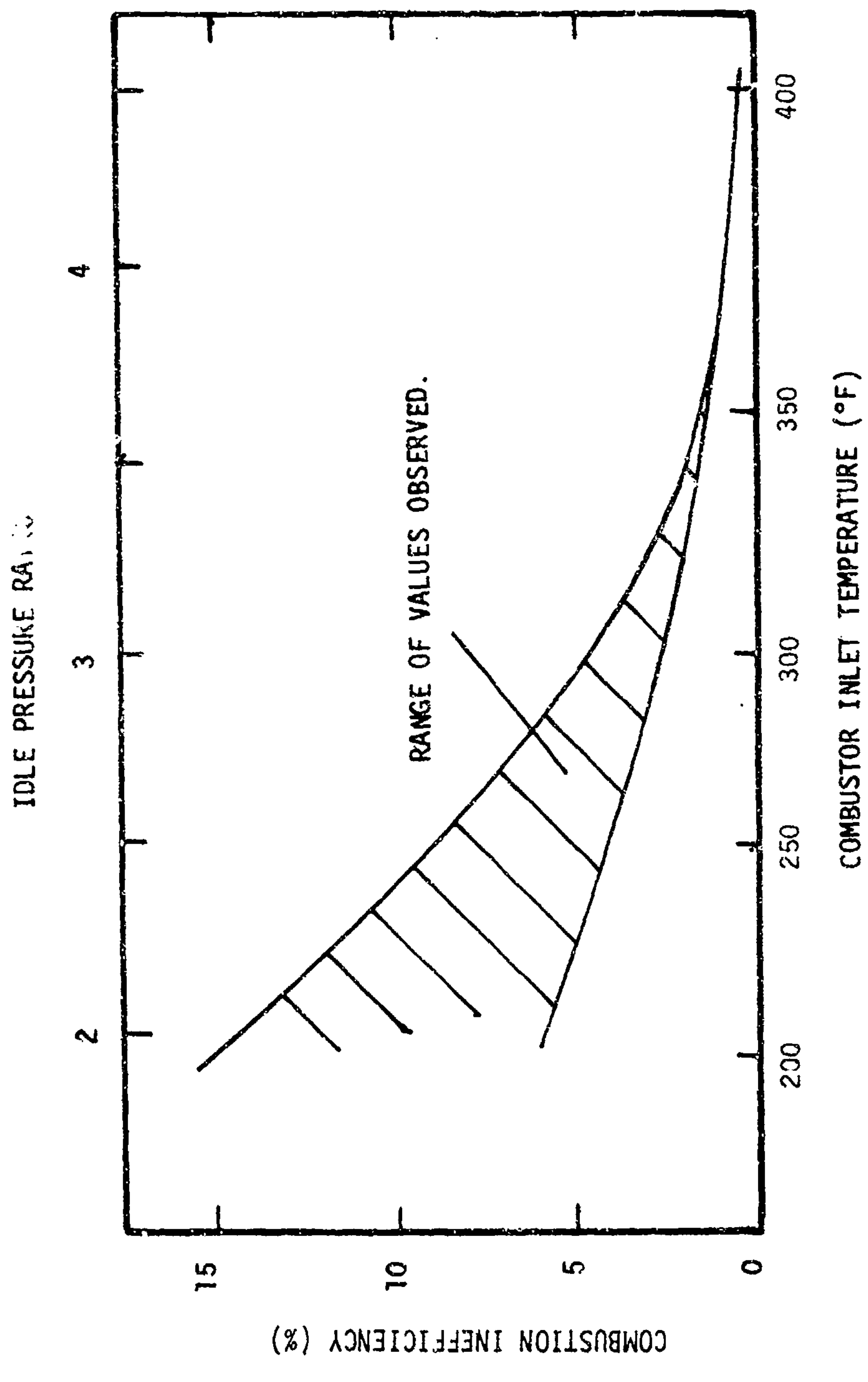

Figure 1. Combustor Inlet Temperature Effect on Idle Combustion Inefficiency

emission indices to increase sharply as shown in Figure 2 (Reference 6). Because of this strong relationship, the proposed USAF emission goal for NO_x (Reference 7) is dependent on engine design through the NO_x-T_3 relationship of Figure 2. It is further apparent that economic considerations for stratospheric flight require cycles with high T_3 values and this leads to increased release of NO into the stratosphere. The relationship between important parameters for stratospheric flight (Mach number and engine pressure ratio) and NO_x emission is shown in Figure 3.

Consider now the predictions of emission levels for engines employing emission control. If it is assumed that the NASA Clean Combustor Program and other federally funded efforts develop the technology to meet their goals, the levels listed in Column A of Table I will be achieved in the early 1980's. These levels are, in general, comprised of relatively consistent goals and standards existing and under consideration by Federal Agencies (References 2, 4 and 7). It should be noted that these levels pertain to high pressure-ratio turbine engines of the JT9D and CF6 class. Column B of Table I involves emissions estimates by some investigators (References 8, 9) of burners designed for ultra-low emissions. These burners entail fuel-air premixing and gas-phase burning at very low equivalence ratios.* The reliability, maintainability, and durability of these designs are often seriously

*Equivalence ratio, ϕ, is the fraction of the stoichiometric fuel-air air mixture (.067 by weight) involved in a given combustion operation.

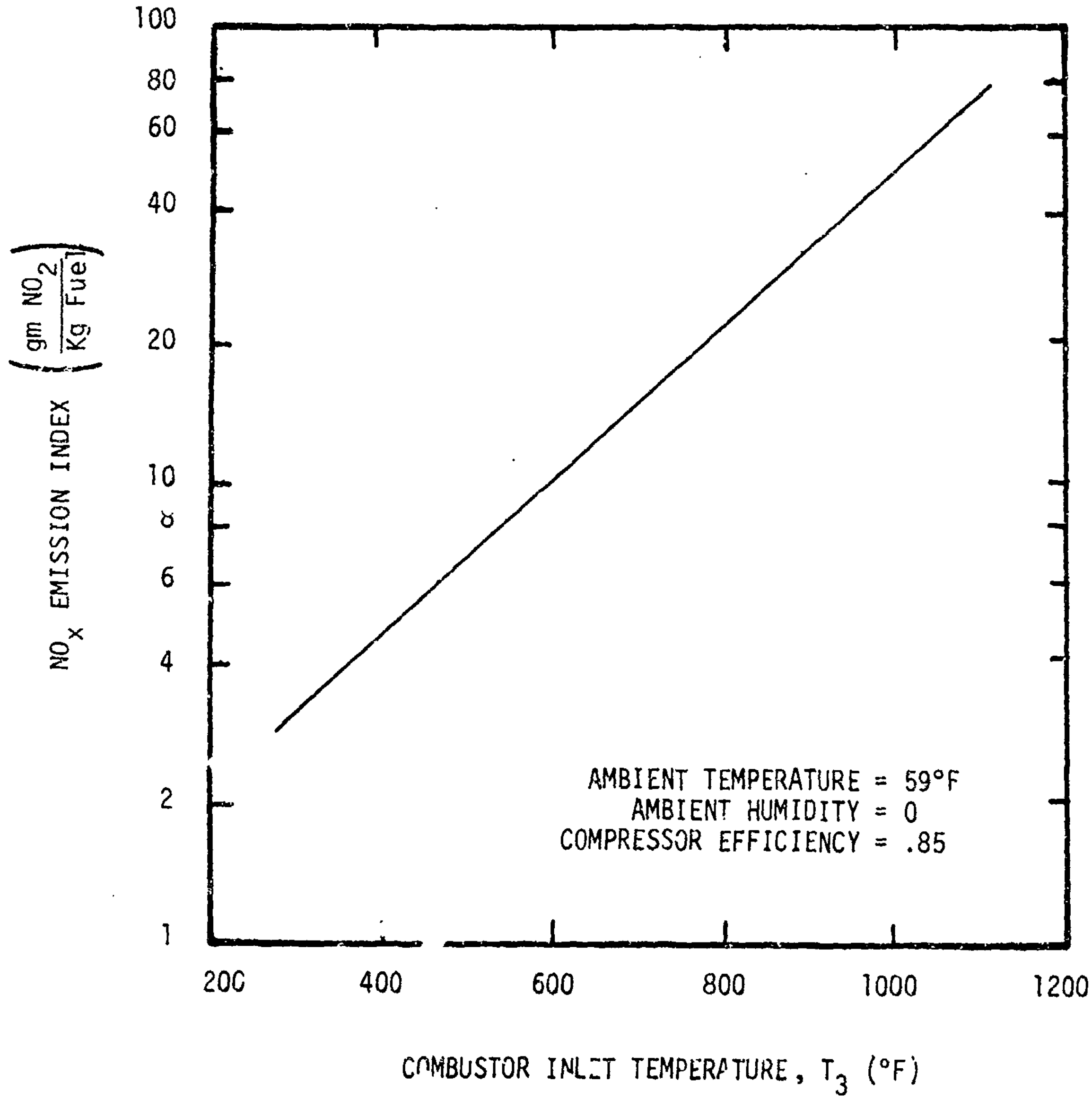

Figure 2. Combustor Inlet Temperature Effect on NO_x Emission

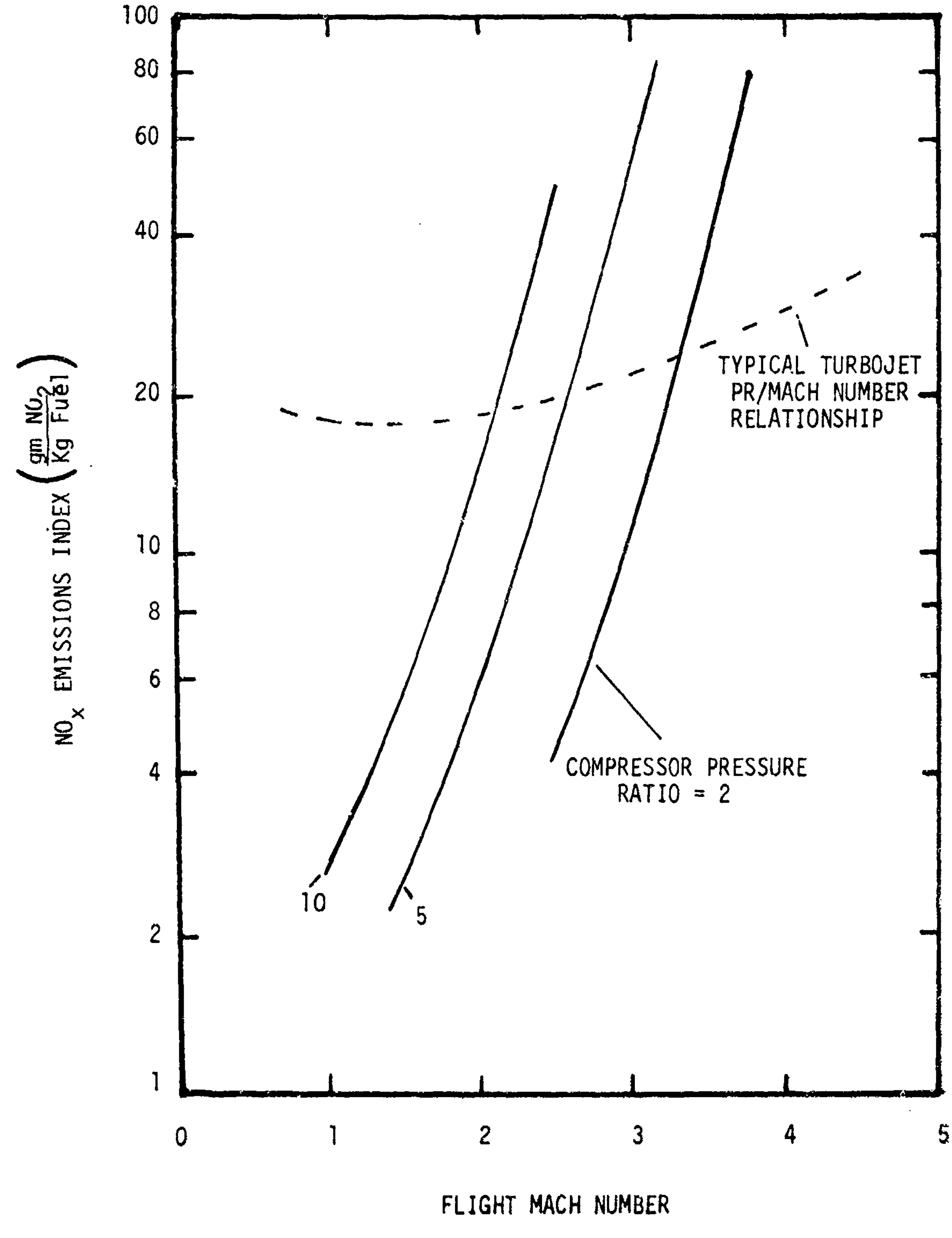

Figure 3. NO_x Emission Characteristics During Stratospheric Flight

TABLE I. PREDICTIONS OF FUTURE EMISSION LEVELS ATTAINABLE IN THE EARLY 1980's

	A Expected by Federal Agencies*	B Ultra-Low-Emission Burners (8,9)
Idle Combustion Inefficiency	.5%	.3%
Typical Full-Power NO_x Emission Index†	15.	.5

*Representative of EPA Standards (Reference 2), AF Proposed Goals (Reference 7), NASA Clean Combustor Goals (Reference 4)

† Class of engines with a pressure ratio of 25.

questioned.

An additional approach to a low emissions burner, the "catalytic combustor," has recently been identified. Although little documentation currently exists, many of the serious problems identified with the low-equivalence-ratio gas-phase combustors may not be encountered with the catalytic combustor because of the way in which it operates. This will be discussed further in Section II.

The investigation reported here was intended to provide basic information for a preliminary assessment of the catalytic combustor concept. The catalytic bed was designed and supplied by Engelhard Industries of Menlo Park, New Jersey. The balance of the combustion system was designed and constructed at the Air Force Aero Propulsion Laboratory (AFAPL). Testing was performed in Room 20, Building 18-C, of the AFAPL. The scope of the study was to determine:

a. Emission characteristics; in particular, whether at simulated high power conditions the NO_x emission would be substantially lower than that of conventional gas-phase burners.

b. Systems operational parameters which might indicate insurmountable problems with the concept.

Insofar as the NO_x was to be specifically investigated, the catalytic bed itself was designed by Engelhard to operate well at high inlet temperature conditions. The off-design conditions reported here are not indicative of results ultimately attainable.

SECTION II

PRINCIPLES OF OPERATION

Gas turbine engines operate quite fuel lean. Temperatures entering the turbine are limited, by material and cooling limitations, to about 2700°F (1755°K). Since inlet temperatures are 700-1000°F (644-811°K) at high-power conditions, this corresponds to a combustor temperature rise of 1400-2000°F (1033-1365°K) or an overall JP-4 fuel-air ratio of .025 - .030 (less than one-half the stoichiometric ratio of .067). Because of stability and combustion efficiency considerations, however, certain regions of the combustor are designed to operate at, or very near, stoichiometric. A well-mixed recirculation region within the dome of the combustor called the primary zone is the principal region of stoichiometric burning in conventional burners.

The known reactions of NO_x formation in the gas phase are very temperature sensitive. In fact, only above 3000°F (1922°K) are the reactions fast enough to produce significant amounts of NO. It follows, therefore, that if the combustor were operated with no region where the fuel-air ratio exceeded levels of about 60% stoichiometric (ϕ = .6), nitrogen oxides would not be formed in appreciable quantity. This is the principle behind and means of operation for low-equivalence-ratio gas-phase burners mentioned previously. It is also the way in which the catalytic combustor operates.

Figure 4 graphically displays the axial temperature profiles of conventional, low-emission gas-phase, and catalytic combustors. It is seen that the only appreciable difference in the low-emission gas-phase and catalytic combustors involves the presence of the catalytic bed itself.

Consideration of the basic catalytic combustion system tested at AFAPL further illustrates the catalytic combustor concept. In this system the fuel-air ratio entering the catalytic bed was uniform and below .03 (ϕ = .45). A system of plates with a hole pattern intended to create a uniform velocity profile was placed between the fuel introduction point and the catalyst bed. Additional air was passed around the outside of the combustor so that the pressure bearing outer walls would be kept at safe temperatures. Mixing of the two streams in the exhaust section kept that section at reasonable temperatures as well.

A number of potential advantages (aside from low emissions) and disadvantages of catalytic combustion are apparent. Potential advantages are:

a. Instabilities associated with gas-phase combustion at low values of ϕ are likely to be greatly reduced by the presence of the catalytic bed. The "thermal inertia" of the bed is a significant means of damping chemical reactivity fluctuations due to combustor inlet changes and, hence, extends the blow-out range. A quantitative idea of this thermal inertia can be obtained by comparing

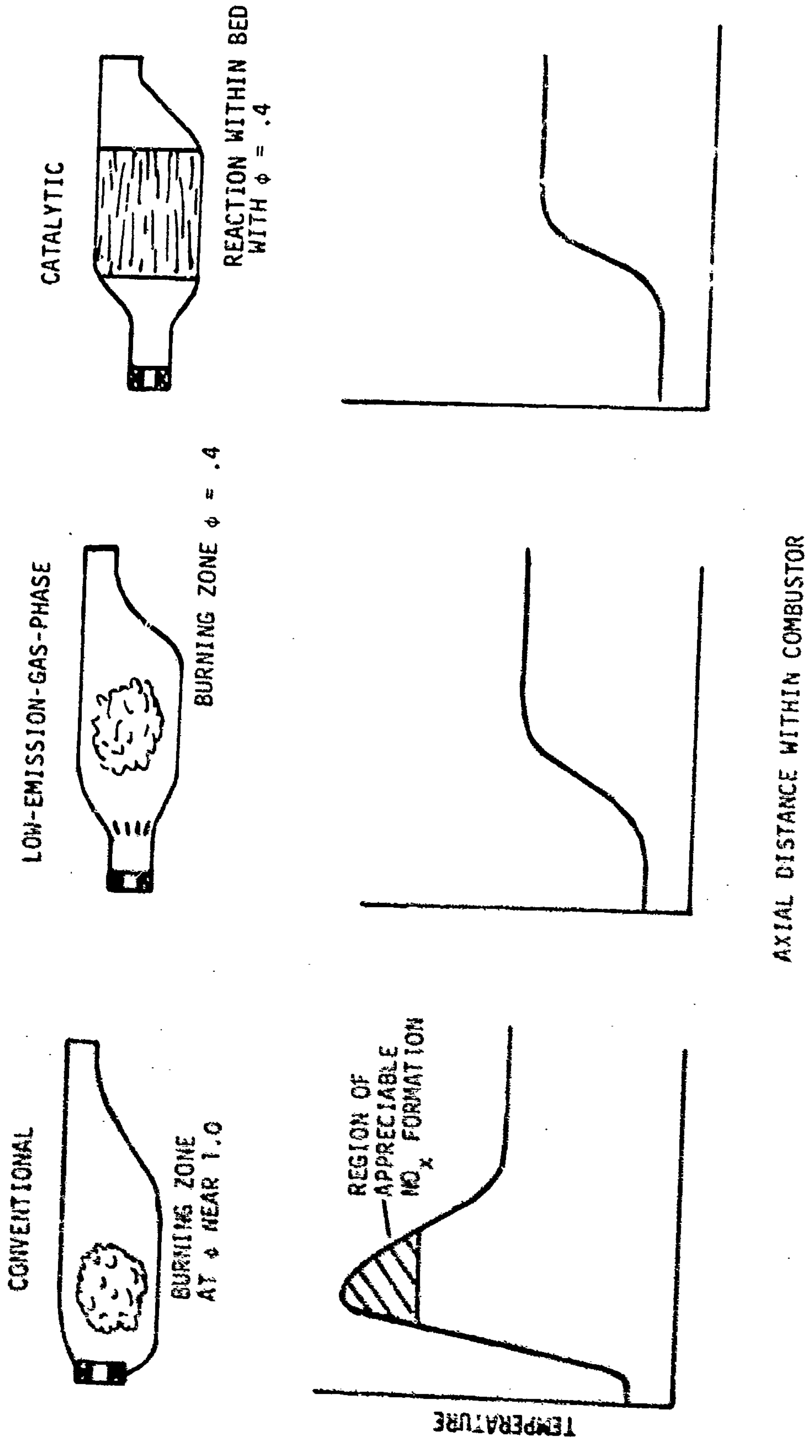

Figure 4. Axial Temperature Pro[illegible] of Various Combustor Types

the volumetric specific heat of the catalytic bed with that of a conventional combustor. The bed value is higher by the factor

$$\frac{\rho_s C_{ps}(1-\epsilon)+\rho_g' C_{pg}' \epsilon}{\rho_g'' C_{pg}''} = 620. \qquad (2)$$

where

ρ_s = solid bed material density (taken to be 217 lbm/ft^3)

C_{ps} = solid bed material specific heat (taken to be .183 BTU/lbm °F)

ϵ = bed void space (taken to be .5)

ρ_g = density of reacting mixture (taken to be that of air)

C_{pg} = specific heat of reacting mixture (taken to be that of air)

(') = prime represents values evaluated at 2400°F (1589°K), and p = 10 atm.

(") = double prime represents values evaluated at 4000°F (2478°K), and p = 10 atm.

b. Combustion efficiency can be optimized by proper design of the catalytic system. Trade-offs with catalytic bed pressure drop and heat release rate are possible. Estimates of efficiency attainable under idle operation, where CO and C_xH_y emission will predominate, are not presently available.

c. Turbine inlet pattern factor can be better controlled because the catalytic bed temperature and velocity profiles will be more uniform than in the case of gas-phase combustors, which depend

strongly on swirling, highly ... flow patterns.

Potential disadvantages are:

a. Additional complexity is necessary because fuel and air must be premixed and introduced to the bed with a uniform velocity and fuel-air ratio. Uniform velocity is necessary as approaching regions of low or negative velocity will cause a flame to propagate upstream and destroy the fuel introduction mechanism. This we have called "flashback." Additional problems may be encountered because of "preignition". In this case, stagnation regions of the hot fuel-air mixture flow (in modern engines temperatures in this region can approach 1100°F) in the vicinity of metallic surfaces may cause ignition upstream of the catalytic bed face and subsequent damage. Uniform fuel-air ratio is required because local temperatures within the catalytic bed will be influenced by local values of equivalence ratios. Significant deviations from the overall fuel-air ratio can cause "hot spots" where temperatures may exceed the limits of the bed.

b. Maintainability and reliability are likely to be lower than present day combustors. However, a comparison with future designs involving premixing, staged combustion, and possibly, variable geometry cannot be made at this time. Similarities between the low-equivalence ratio and catalytic combustors indicate that eventual maintainability may be comparable for the two approaches.

but because of the advantages already mentioned, catalytic combustor reliability may be more favorable.

The fact that many practical problems have not yet been approached (i.e. starting, lifetime determination, catalyst poisoning by fuel trace constituents, etc.) creates additional uncertainty. Before these are solved, the more fundamental trade-offs of advantages and disadvantages discussed above require investigation. Fundamental studies of system behavior with variation of the following parameters are required:

a. Fuel-air ratio

b. Combustor inlet temperature

c. Entrance velocity and heat release rate

d. Pressure

Testing must be conducted under realistic conditions. In addition to the values of the parameters listed above, this applies to the type of fuel and scale of the test.

SECTION III

EXPERIMENTAL

This section describes the hardware used to test the catalytic combustor. Discussion is organized into facility capability, general description of the combustion system, fuel-air mixing, catalytic unit, measurements made, and fuel characterization.

1. FACILITY CAPABILITY

The AFAPL Single Combustor Rig Facility is capable of providing up to 7.5 lbm/sec (3.4 kg/sec) of unvitiated air at pressures up to 250 psig (18 atm) and temperatures up to 850°F (727°K). Three Ingersol Rand compressors with interstage cooling supply air to a gas-fired preheater which raises air temperature to the desired level. Accurate inlet pressure is maintained by automatic bleed-line control near the combustor inlet. Exhaust flow rate is controlled manually through a remotely operated exhaust plug.

2. COMBUSTION SYSTEM

A special combustion system was designed and constructed for this test. Requirements of the system were:

a. Provide a uniform fuel-air mixture for the catalytic combustor to prevent hot spots.

b. Insure that the velocity approaching the catalytic bed was uniform to avoid flashback.

c. Provide a means of cooling all pressure bearing components so that high pressure levels may be achieved.

The system shown in Figures 5 and 6 was intended to meet these objectives. Total air flow entering the system was measured with the total flow venturi (2 inch throat) before being split into an inner flow and an outer cooling flow.

The inner flow and, hence, the flow split ratio, was determined by a second venturi (1.5 inch throat) before entering the carburetor. The resulting fuel-air mixture was then reacted within the catalytic unit.

The outer flow proceeded through the space between the outside pressure-bearing walls and the inside components. Regulation of the air split between the inside and outside passages was attained by altering the position of windows which could be controlled without rig disassembly. Window movement was accomplished by rotation of a can-like structure to which window shutters were attached. A shaft protruding outside the rig turned the can through a bevel gear arrangement. Figure 7 shows the window control. For these tests, the ratio of cooling to inner flow was kept at approximately 1/3. Variation of this parameter did not alter the results obtained.

Cooling of the catalytic unit outer duct was successful. In addition to the convective cooling, a gold foiled liner was placed within this unit to reduce the radiative heat transfer from the hot

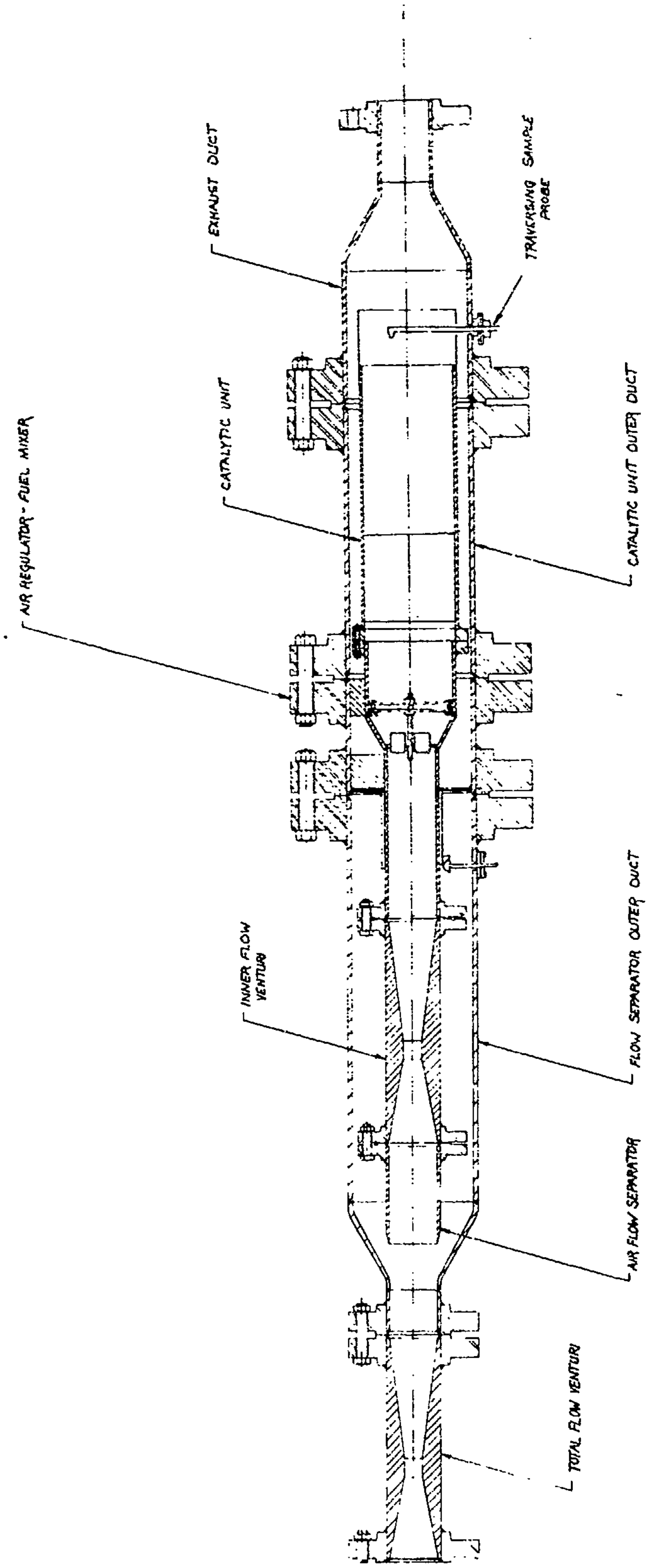

Figure 5. Catalytic Combustor System Assembly

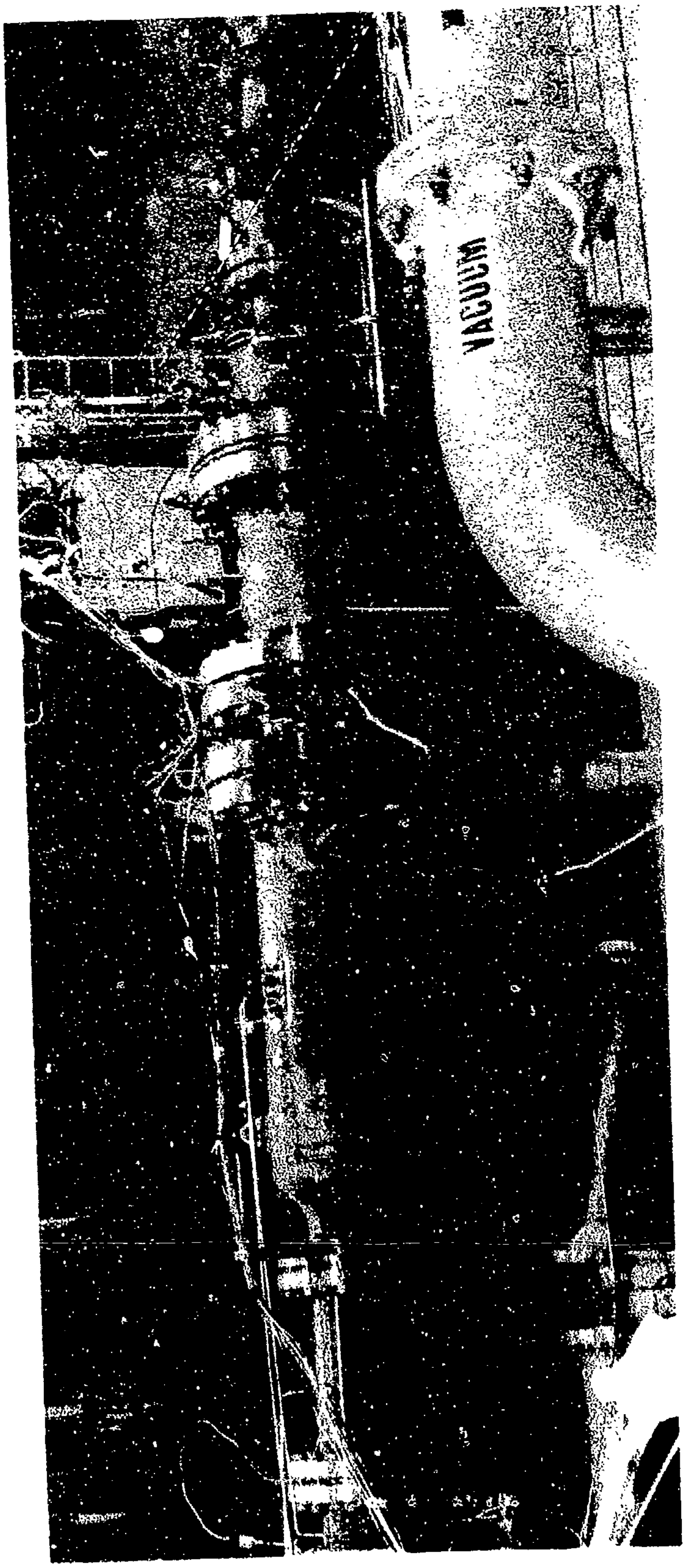

Figure 6. Overall View of the Catalytic Combustor System

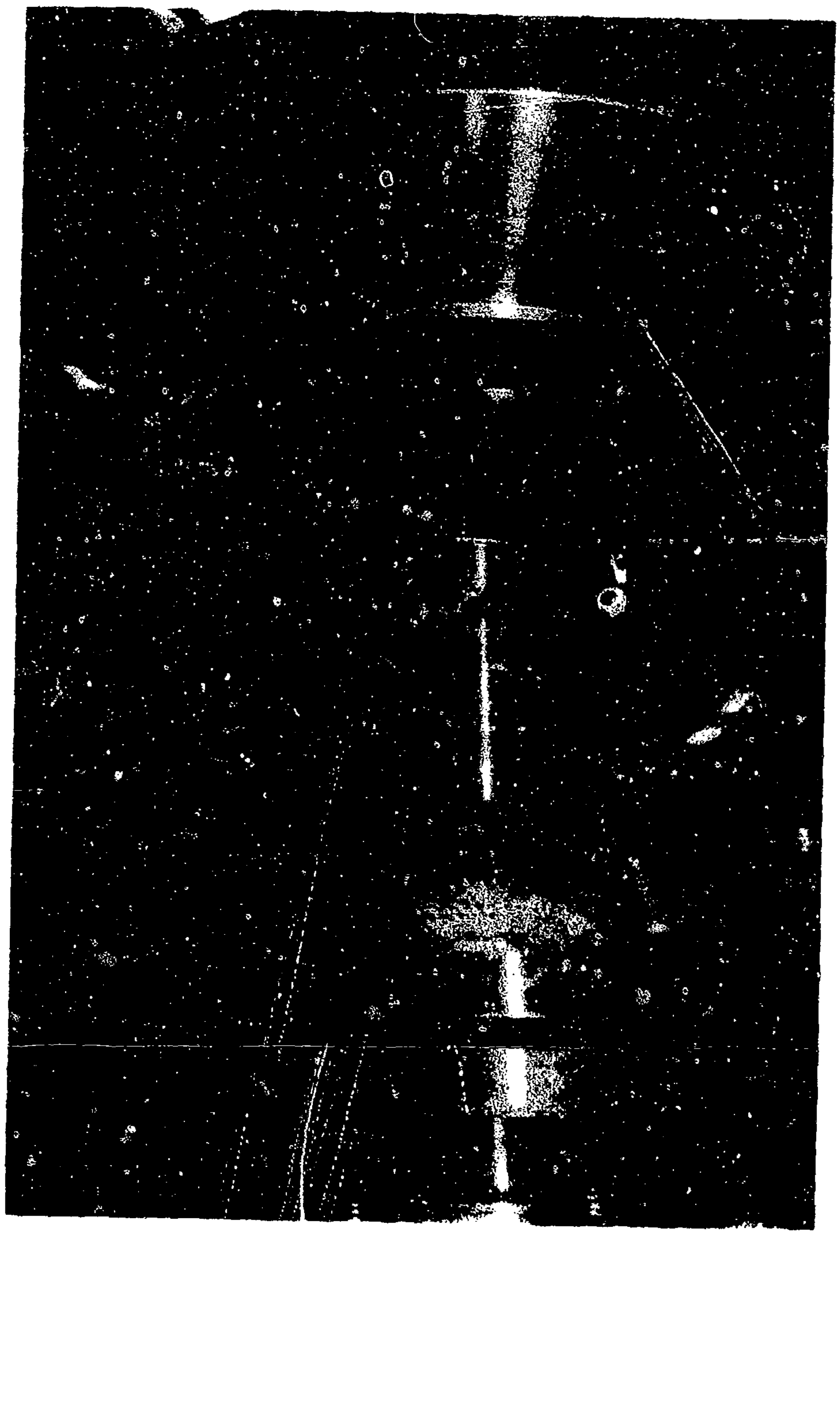

Figure 7. Flow Control Mechanism Viewed with Flow Separator Outer Duct Removed

catalytic unit. The temperature of the outer duct was measured to be less than 1100°F (866°K). The exhaust duct was at temperatures lower than the ideal mixed temperature of the inner and cooling flows because the system geometry allowed the cooling air to remain nearer the outer duct.

3. FUEL-AIR MIXING

A number of different techniques were tried to achieve the uniform fuel-air ratio and velocity for introduction to the catalytic unit. Initial testing involved introduction of fuel through a T56 engine nozzle in the upstream direction with the subsequent flow passing through a plate with a hole distribution designed to cause uniform velocity flow downstream of that location. This concept was initially suggested by technician Glen Boggs and has come to be called the Boggs carburetor.

The principal drawback to this development was that the uniform fuel-air ratio could be destroyed at flow conditions other than those normally used. To remedy this, a technique involving direct air-fuel mixing (without the use of spray nozzles) was developed. In this case, upstream fuel injection was made into three NASA 1-1/4-inch-diameter swirl cans.* This fuel injection point was at the beginning of a transition section from 4 inch ID to 7 inch ID pipe (see Figure 8). The fuel-air mixture then passed through two identical

*The use of these swirl cans was made possible by the kind cooperation of Mr. Robert Jones, NASA Lewis Research Center, Cleveland, Ohio.

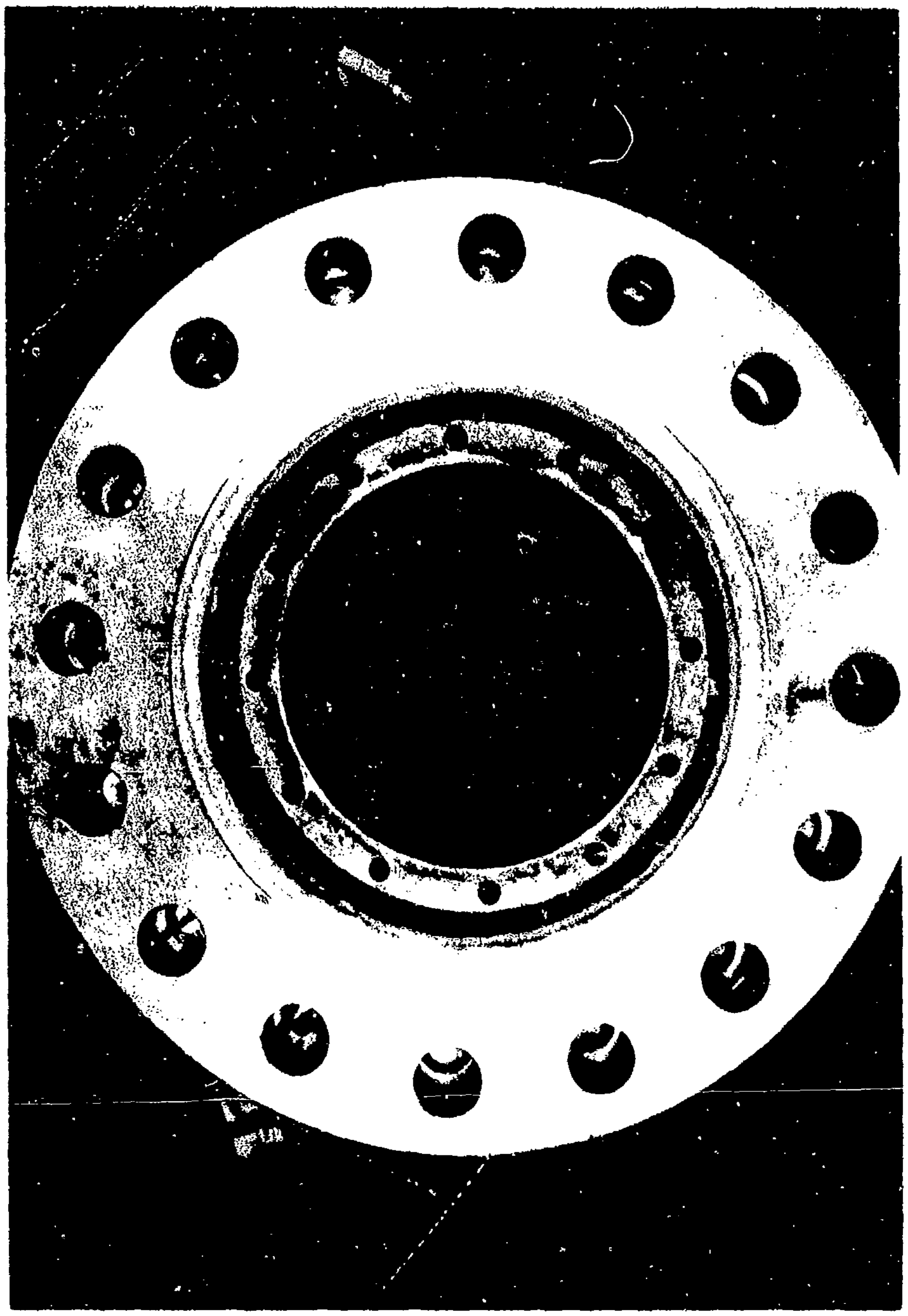

Figure 8. Carburetor Attachment Location and Duct Expansion

"flow distribution" plates with the hole locations not coincidental. This fuel introduction system was named the modified Boggs carburetor and is shown in Figure 9.

Preliminary testing of the modified Boggs carburetor at atmospheric pressure indicated a velocity distribution with mean flow fluctuation of less than 20%. A high degree of turbulence was apparent. Water spray tests indicated a reasonable fuel-air mixing as shown in Figure 10. Liquid collection at the bottom of the duct is thought not to occur for the higher temperatures and more volatile JP-4 fuel encountered during actual burning. The uniform fuel-air mixture was also indicated during runs with combustion by measuring exhaust concentration of all carbon containing species. Uniform distribution of such a carbon concentration at the exhaust indicates a uniform inlet fuel-air distribution. Figure 11 shows a typical result indicating excellent mixing. Additional confirmation at this same operating point is gained by examining the radial temperature profile. Figure 12 shows that data are in agreement with the calculated exhaust temperature; fall-off at the outer radii is due to convective heat loss to the cooled walls and radiation heat losses to the wall which is within 1/2 inch of the thermocouple.

The modified Boggs carburetor did encounter two significant problems. First, at higher pressures and lower inlet temperatures, where droplet vaporization did not readily occur, droplets would

Figure 9. Modified Boggs Carburetor

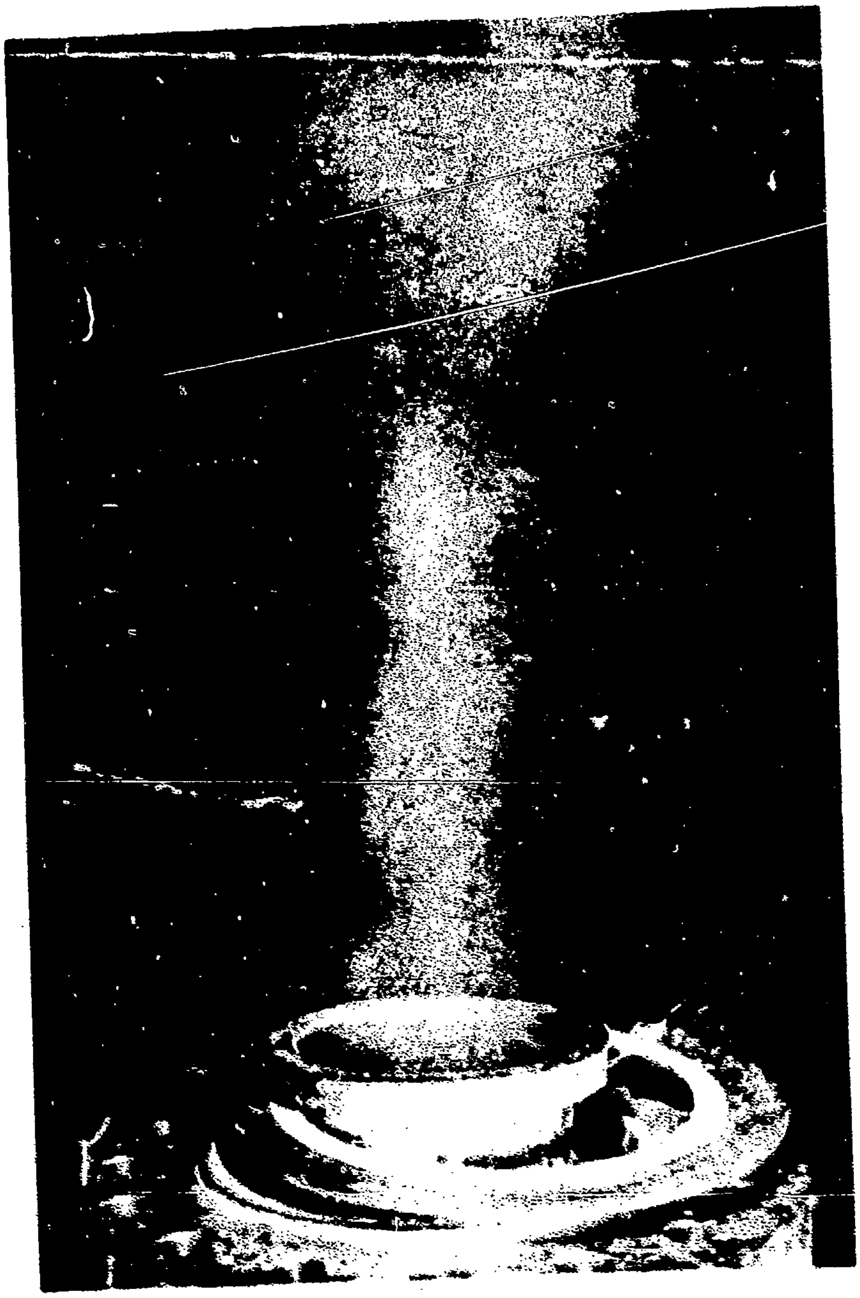

Figure 10. Water Spray Test of Modified Boggs Carburetor

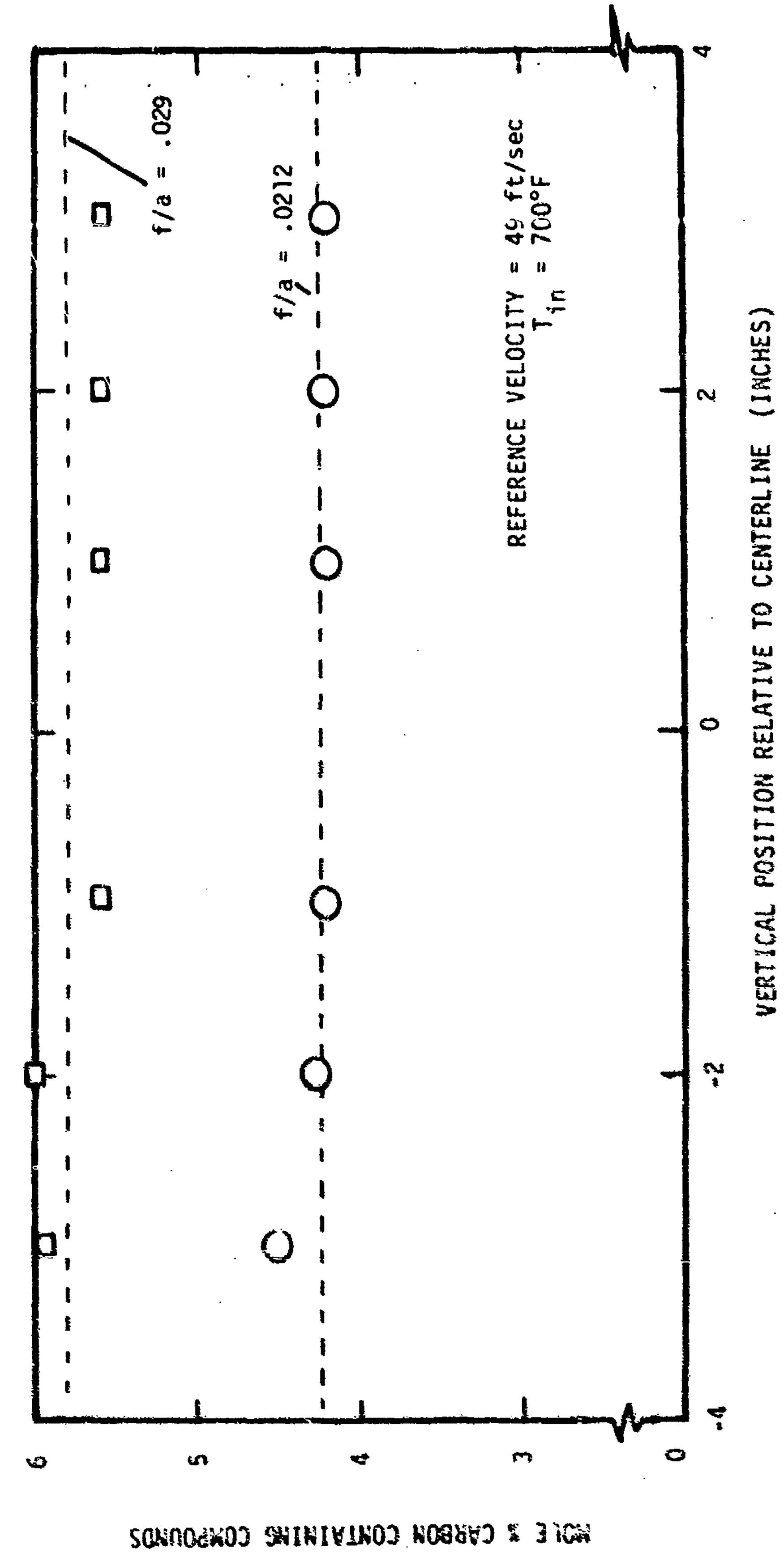

Figure 11. Radial Carbon Balance Check for Uniform Fuel Mixing

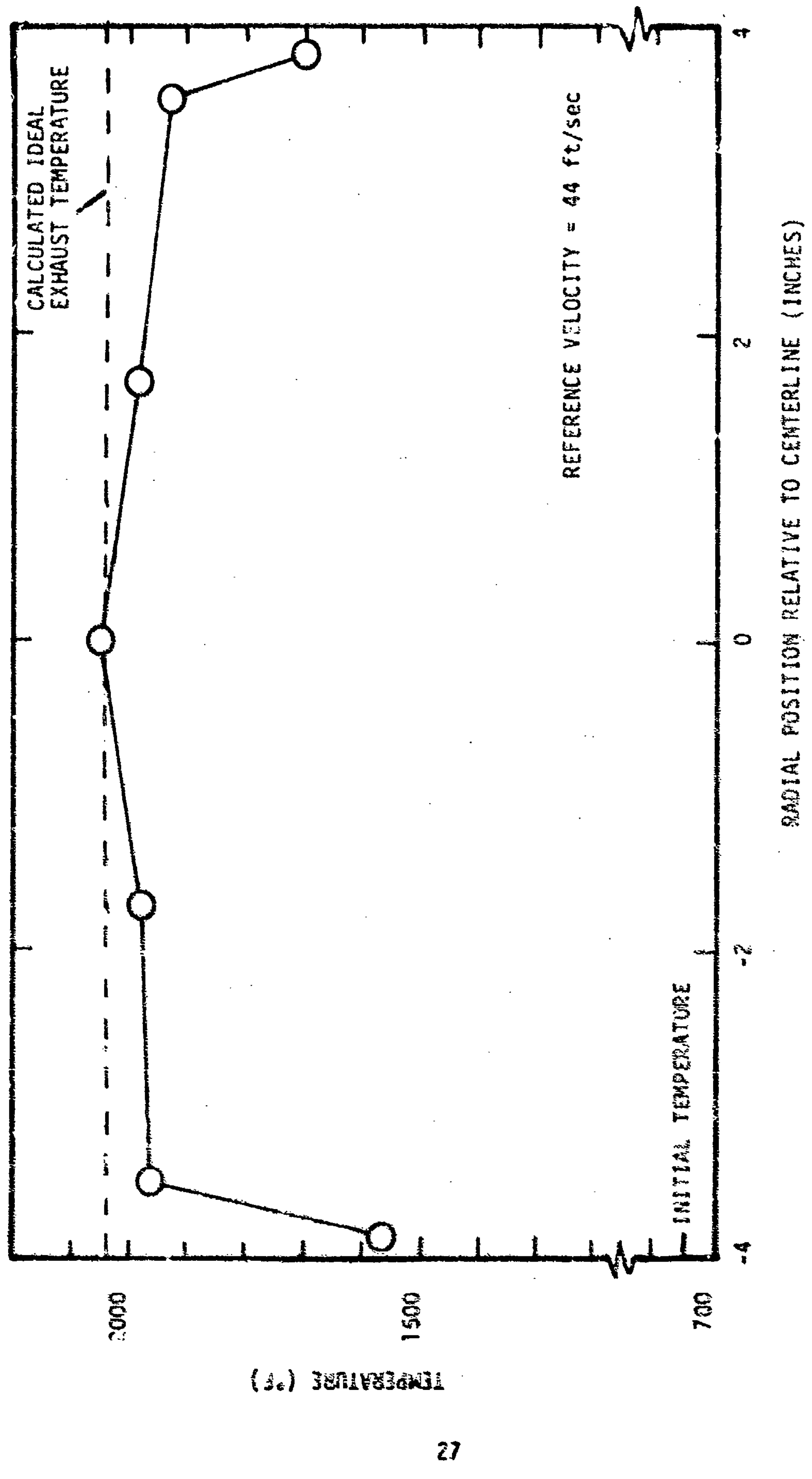

Figure 12. Radial Temperature Profile Indicating Good Fuel Mixing

be forced outside toward the outer diameter of the combustor by the centrifugal motion of the swirl cans. Secondly, at higher inlet temperatures preignition between the two flow-distribution plates became possible and, in fact, did occur. This preignition problem will be further discussed in Section V. Fortunately, the first situation only occurred in a few of the conditions tested in this program.

The modified Boggs carburetor was the configuration used for all results reported in Section IV.

4. CATALYTIC UNIT

The catalytic unit was supplied by Engelhard Industries of Menlo Park, New Jersey. It was contained within an Inconel pipe, 8 inches in outside diameter, 7 inches inside diameter and 24 inches in length. The portion of the pipe occupied by catalyst was seven inches in diameter and seven inches in length (volume was .155 ft^3). Catalyst composition was regarded as proprietary to Engelhard Industries.

The face of the catalyst was positioned within one inch of the flange connecting the unit to the carburetor section. The distance from the flow-distribution plates to the catalyst face was approximately 4 inches. A 17-inch distance existed from the end of the catalytic bed to the end of the 24 inch pipe. It is at this location that exhaust data were taken.

Initial testing with the modified Boggs carburetor at 850°F

(727°K) inlet temperature resulted in a preignition which destroyed the carburetor. A small portion of the catalytic unit was affected by the high temperatures which resulted but the major effect on the catalytic unit was a buildup of scale from the burned stainless steel plates. It was possible to extract this scale with some minor removal (varying from 0 to 3/8 inch) of the catalyst at the front face. All subsequent testing was done at inlet temperatures at or below 750°F (672°K) with a new modified Boggs carburetor.

5. MEASUREMENTS

Mass flows were measured with the venturis previously mentioned and differential pressure transducers. Inlet, exhaust, and differential pressures (across the carburetor, catalytic bed, and flow control windows) were measured with conventional type gages.

Inlet temperatures were determined by a series of chromel/alumel thermocouples both before and after the carburetor. Since a significant pressure drop occurred across the carburetor, the downstream readings were significantly lower. Exhaust temperatures were measured with platinum/platinum-rhodium thermocouples. Initial tests involved two rakes with readings taken at staggered radial positions. These initially confirmed the good fuel-air distribution (see Figure 12) and were later removed because of damage at high temperature. A single five-location thermocouple rake was substituted in their place. This thermocouple was also damaged (see

Figure 13) during final testing at exhaust temperatures of 2400°F (1589°K).

Exhaust samples were extracted with a warm water cooled probe and passed through a heated stainless steel line. The probe was capable of traversing the exhaust plane and was remotely controllable. Some difficulty with long response time in hydrocarbon measurement (especially when levels were below 25 ppmv propane) was experienced, presumably, because of some short unheated portions of the sampling system between the probe and the heated sample line.

Instrumentation used for each measurement is listed in Table II and shown schematically in Figure 14. No difficulties in instrument operation were experienced.

6. FUEL

Standard type JP-4 fuel was used in these tests. Aromatic content was measured to be 11.9 volume percent and the lower heating value was 18,900 BTU/lbm. A more detailed analysis is included as Table III.

Figure 13. Damaged Exhaust Temperature Thermocouple Rake

TABLE II. SUMMARY OF EMISSIONS INSTRUMENTATION

Specie	Instrument*	Range
THC	Beckman Model 402 FID Hydrocarbon Analyser	0-15 ppmC 0-75 ppmC 0-150 0-750 0-1,500 0-7,500 0-15,000
NO, NO_x	Thermo Electron Model 10A Chemiluminescent Analyser	0-2.5 ppmV 0-10 0-100
CO	Beckman Model 315B NDIR Analyser	0-400 ppmV 0-2,000 ppmV
CO	Beckman Model 315B NDIR Analyser	0-7,500 ppmV
CO_2	Beckman Model 315B** NDIR Analyser	0-2.5 % by V 0-10.0 % by V

* Brand names are used in this report for identification only and their mention does not constitute nor imply USAF endorsement.

** Our appreciation to the Department of Transportation for the loan of this instrument during this test.

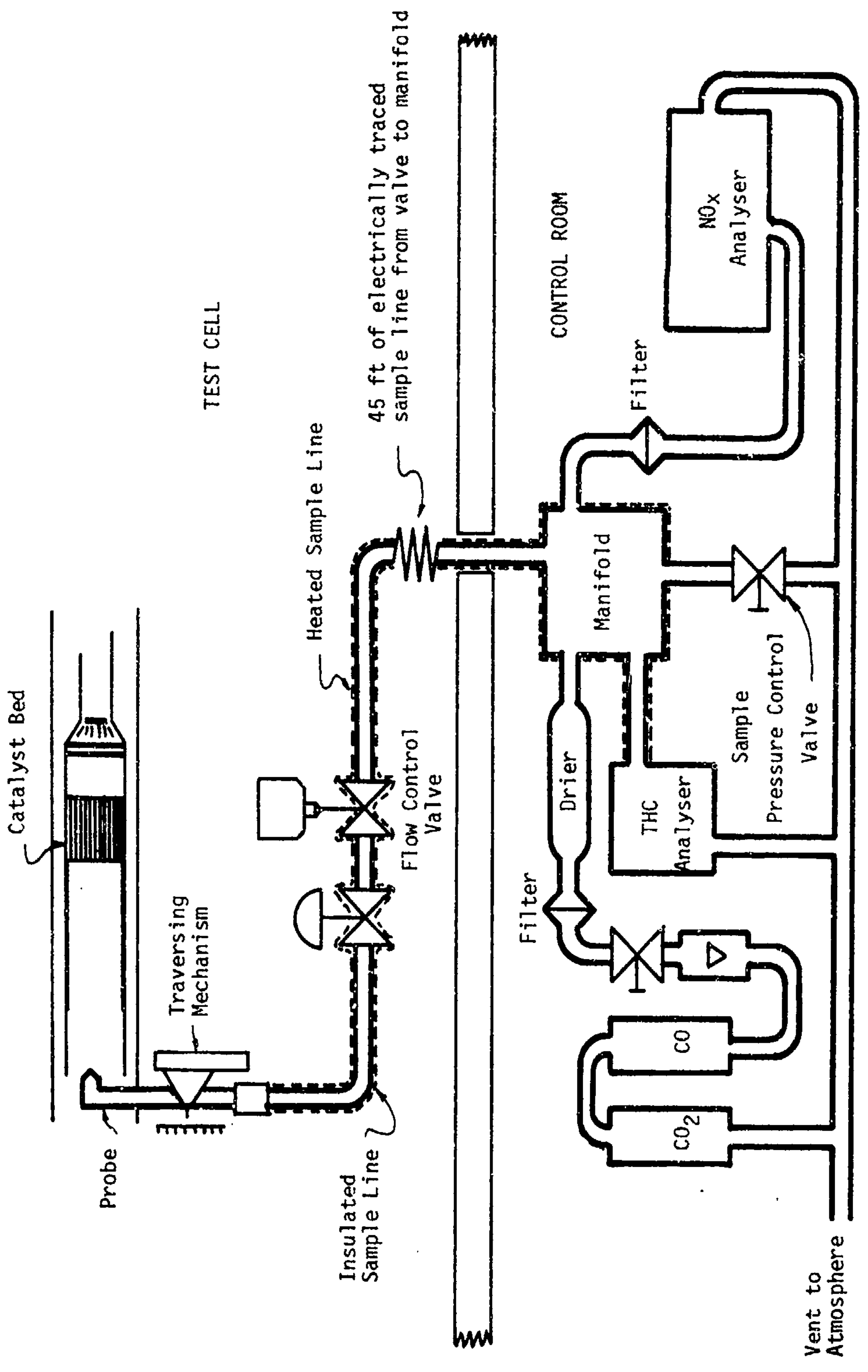

Figure 14. Schematic of Emissions Measurement System

TABLE III. FUEL ANALYSIS

Test	Result	ASTM Test Code*
Gravity °A.P.I.	53.7	D287
Appearance	Clear	-
Odor	Usual	-
Water Reaction	0.0 #1	D1094
Freezing Point °F	Below -72	D2386
Existent Gum (mg/100 ml)	0.8	D381
Total Sulfur, % Wt.	.041	D1266
Vapor Pressure, P.S.I. @ 100°F	2.6	D323
Aniline Gravity Constant	7,142.	D1415
Smoke Vol. Index	62.9	D1322 (modified)
Aromatics %	11.9	D1319
Olefins %	0.8	D1319
Neut. No.	.007	D974 (modified)
MIL-I-27686 Icing Inhibitor (% Vol)	0.103	FTMS 791, method 5327
Initial Boiling Point, °F	127	D86
10%	206	
20%	236	
50%	308	
90%	427	

See Reference 10 for test definition.

SECTION IV

RESULTS

Initial testing was oriented toward investigation of fuel-air distribution and establishment of a "typical operating point." Results of the first of these were already discussed in Section III. The typical operating point was intended as a condition to be reproduced after each day's testing to insure against loss of catalyst activity due to operational influences or degradation. These conditions should be near those where the system becomes inefficient, so that parametric changes are sensitive. The condition chosen was:

T_3 = 700°F (644°K)

P = 90 psig = 7.1 atm

V_{ref} = 44 ft/sec (13.7 m/sec)

f/a = .0212

The reference velocity, V_{ref}, is the velocity at the inlet to the catalyst face. Calculated exhaust temperature for these conditions is 2000°F (1366°K).

Fortunately, this point was established early in the program. Assurance that the previously mentioned incident of bed damage had not influenced catalyst performance was gained through repetition of this point. Further, no significant deviations were noted in the emissions at this point over the entire 28 hours of testing conducted.

Before discussing variations due to some of the important

parameters previously cited, it should be noted that two of the measured quantities were near or below levels which could be accurately sensed by the instruments used.

a. Measured NO_x values in all cases were below 2 ppmV. A definite trend of increasing NO_x level for increasing exhaust temperature was noticed but, again, this was still below the very low level of 2 ppmV. These data are not further reported in this section because of the small impact of such low concentrations.

b. Catalytic bed pressure drops were about 1% of the combustor static pressure ($^{\Delta P}/_{P}$) at 44 ft/sec reference velocity and 2400°F exhaust temperature. At higher reference velocities, the $^{\Delta P}/_{P}$ increased to about 2% at 65 feet/sec. Other trends of $^{\Delta P}/_{P}$ could not be accurately sensed with the differential pressure gage used and are not further analyzed in this report.

As previously mentioned, the important parametric variations are fuel-air ratio, inlet temperature, reference velocity, and pressure. Results for these variations will be discussed separately below. An additional section involving other observations is also included.

1. FUEL-AIR RATIO

Fuel-air ratio was determined from separate measurements of fuel flow and air flow. Independent confirmation of this measurement was determined by summing the concentrations of carbon

containing compounds, as in connection with Figure 11. During tests varying fuel-air ratio, both reference velocity and inlet temperature were held constant. Results are indicated in either emission indicies of CO and C_xH_y or as combustion efficiency (see Equation 1). Emission indicies were numerically averaged values over the exhaust plane. Each point indicates the average of six measurements.

Figure 15 illustrates the emission index variation. It is seen that for this 700°F (644°K) condition, emissions sharply increased at fuel-air ratios less than .0212 or exhaust temperatures less than 2000°F (1366°K). It is also noted that the emission trend of CO begins to level off at the poor efficiencies while that for C_xH_y seems to be still increasing. One might speculate that further efficiency decreases would cause a shift of the ratio of hydrocarbon to CO emission indicies. It should be further noted that the CO and C_xH_y emission indicies are shown as leveling at high fuel-air ratios only because of inadequacy of the measurement system to determine lower concentrations at the time this data was taken. A decreasing trend should be expected.

These same data have been translated into combustion efficiency by the use of Equation 1 and are shown in Figure 16. Note excellent combustion efficiency is achieved at exhaust temperatures of 2000°F (1366°K) and above with the inlet temperature of 710°F (648°K).

2. COMBUSTOR INLET TEMPERATURE

Although a calculated exhaust temperature of 2000°F (1366°K)

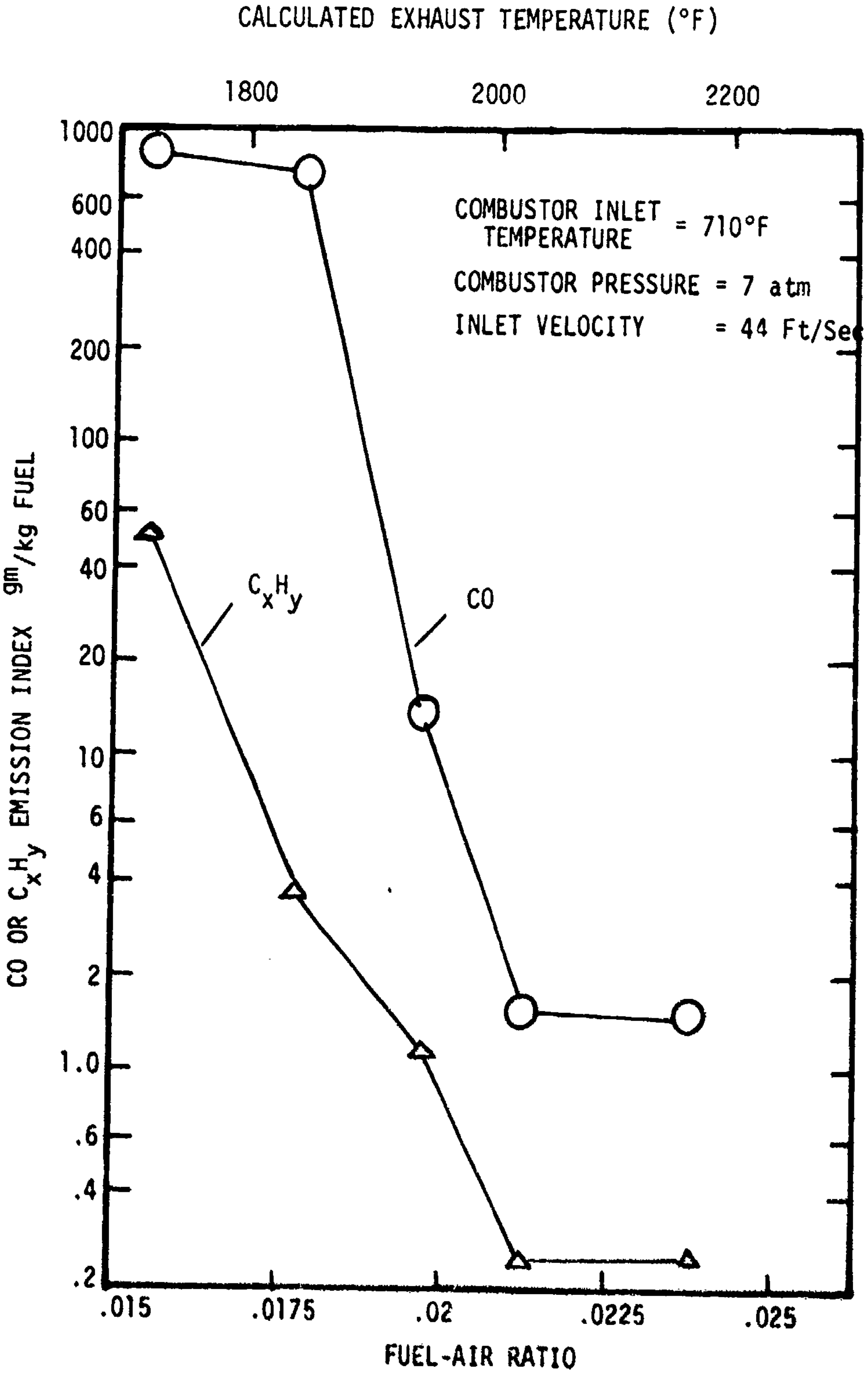

Figure 15. CO and C_xH_y Emission Index Variation with Fuel Air Ratio

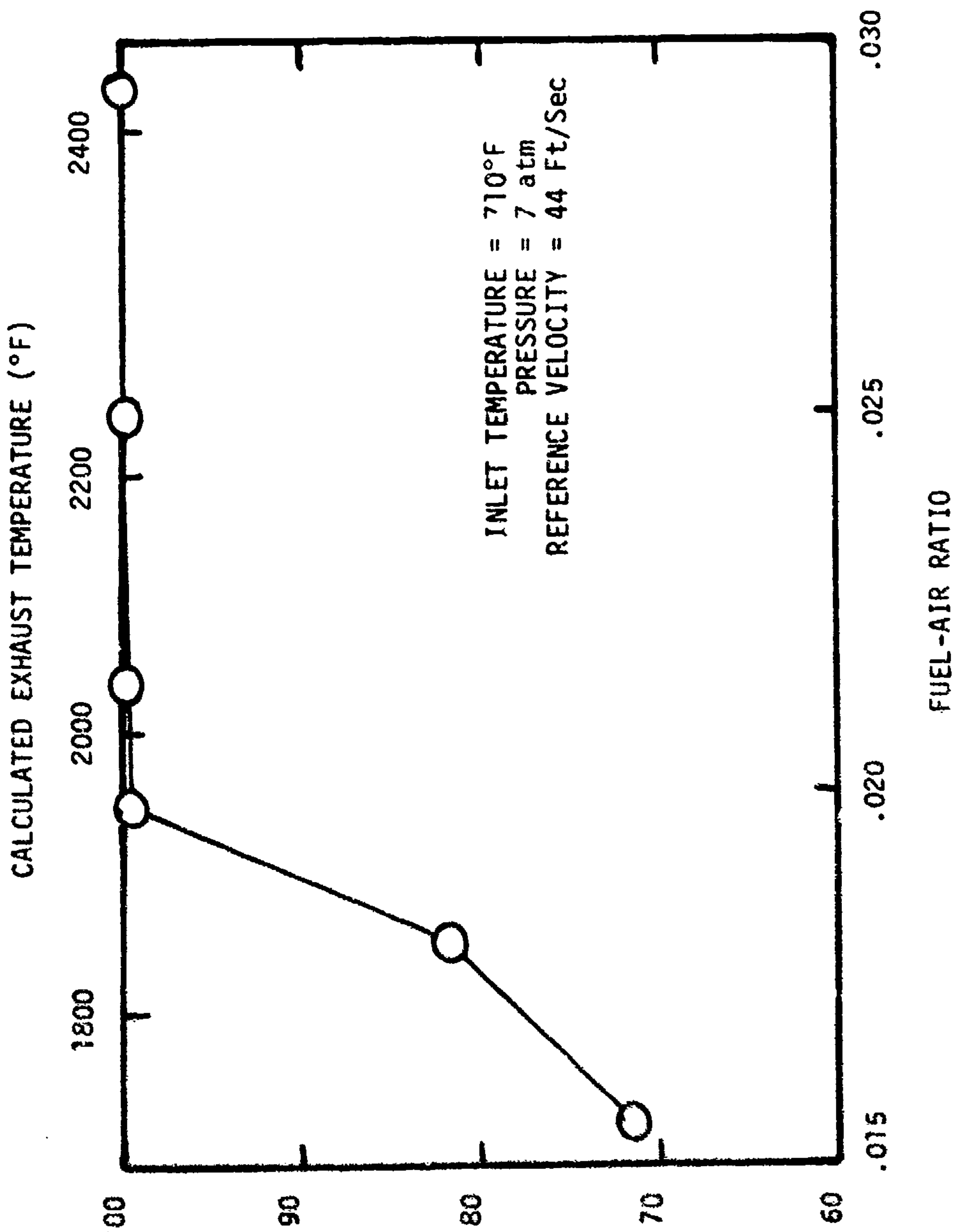

Figure 16. Combustion Efficiency Variation with Fuel-Air Ratio

was sufficient to attain a good combustion efficiency when inlet temperature was 710°F (648°K), no calculated temperature up to 2250°F (1505°K) could be found for efficient operation at 615 or 540°F inlet temperature. Results are shown in Figure 17.

As expected, the strong effect of inlet temperature is apparent throughout the entire range of fuel-air ratios tested. Fuel-air ratios corresponding to 2400°F calculated exhaust temperature were not approached at the lower inlet temperatures because of the odor nuisance and potential hazards near the test cell exhaust at these conditions. The time spent at low inlet temperatures was minimized.

3. COMBUSTOR REFERENCE VELOCITY

In all tests except those about to be discussed, the combustor reference velocity was maintained at about 44 feet/sec (13.7 m/sec). Air flow limitations prevented attaining velocities greater than 70 feet/sec (21.9 m/sec) at the combustor pressure of 75 psig (6.2 atm) used for this test.

Figure 18 shows the efficiency dependence on reference velocity for fuel-air ratios of .0212, .023, and .0267 and an inlet temperature of 700°F (644°K). Efficiency drops off at much lower reference velocities for the lower fuel-air ratios.

4. PRESSURE

Figure 19 shows the data collected at various combustor pressures. Inlet temperature was 700°F (644°K), reference velocity

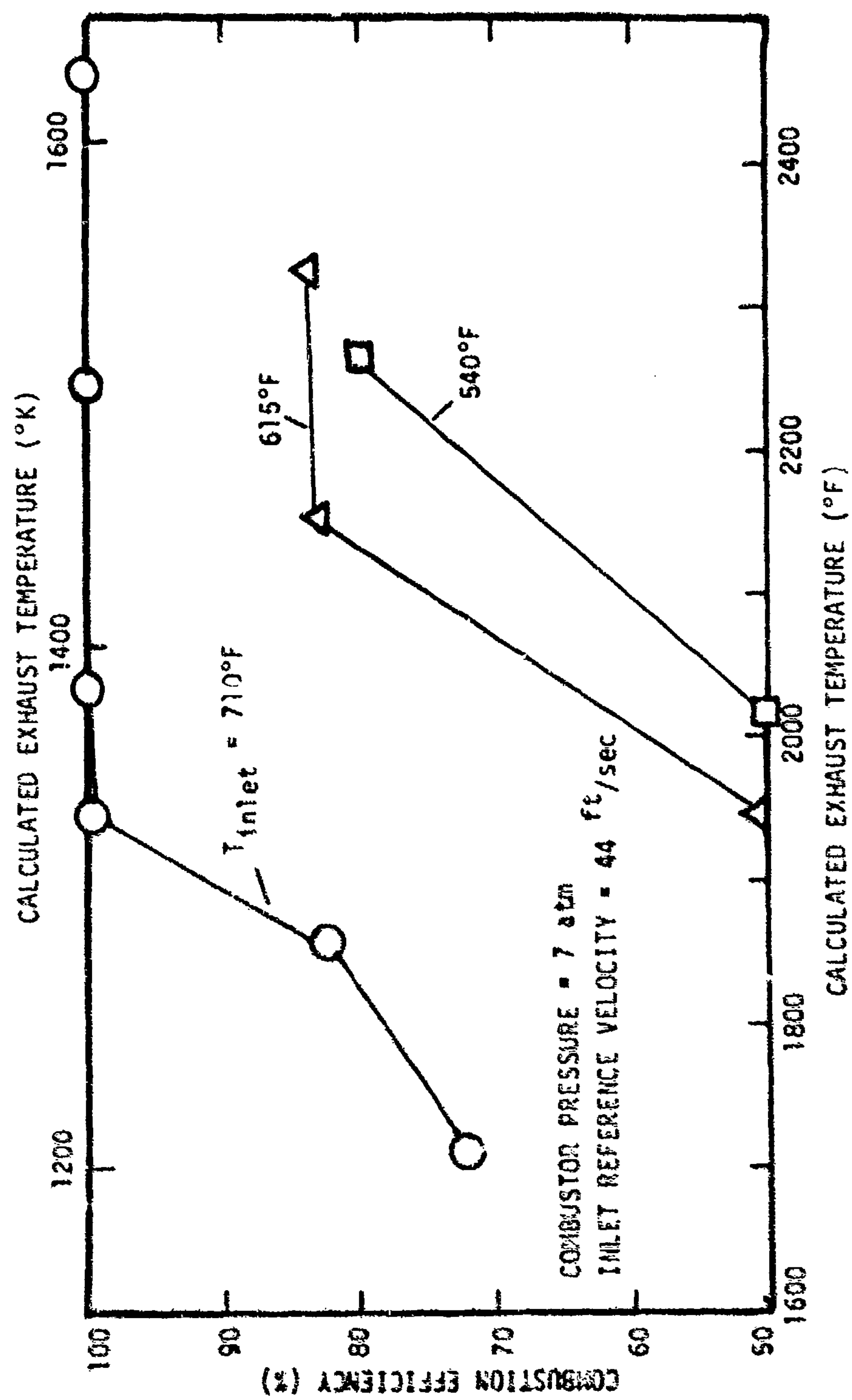

Figure 17. Effect of Inlet Temperature on Combustion Efficiency

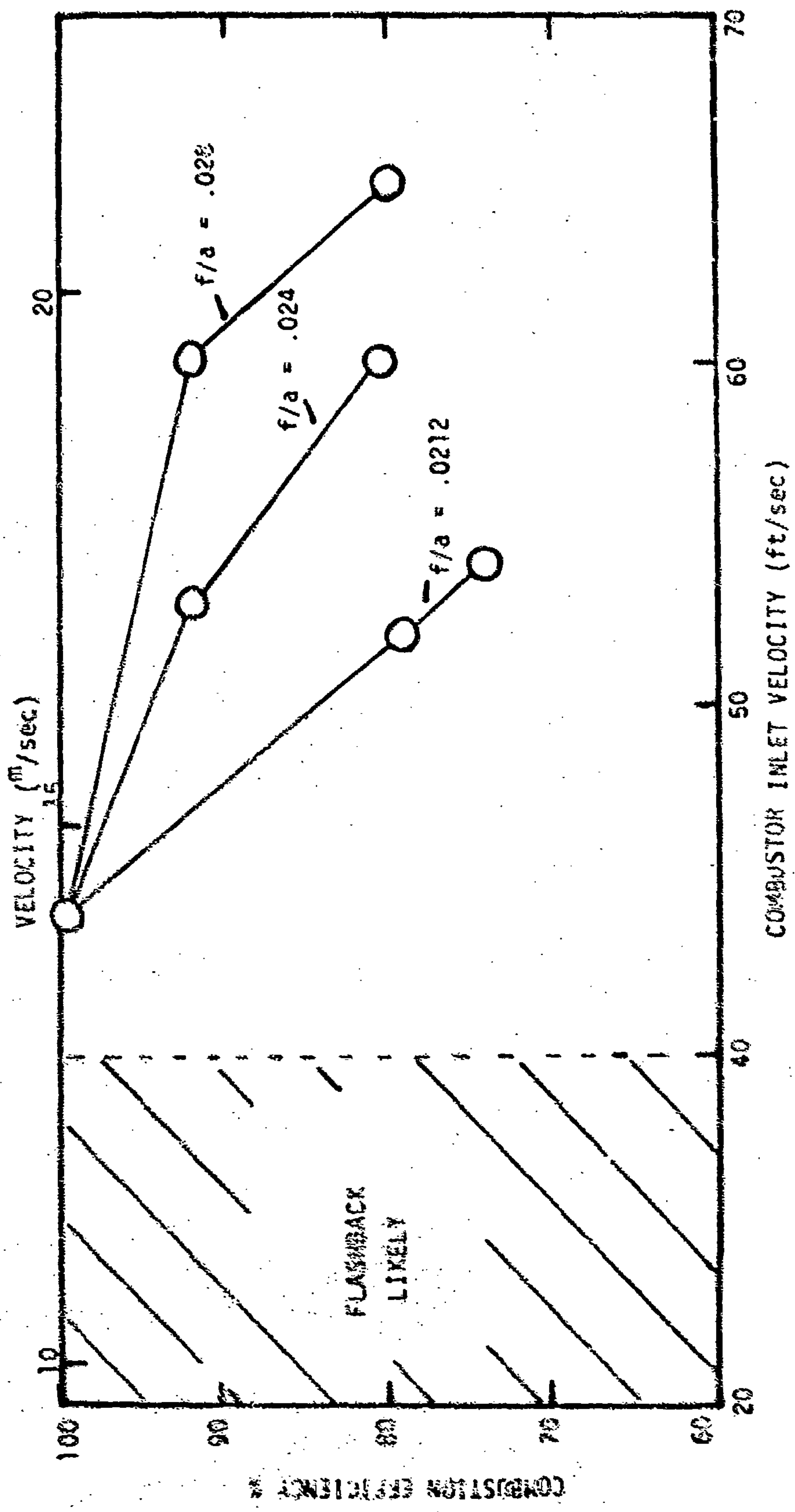

Figure 18. Reference Velocity Effects for Various Fuel-Air Ratios

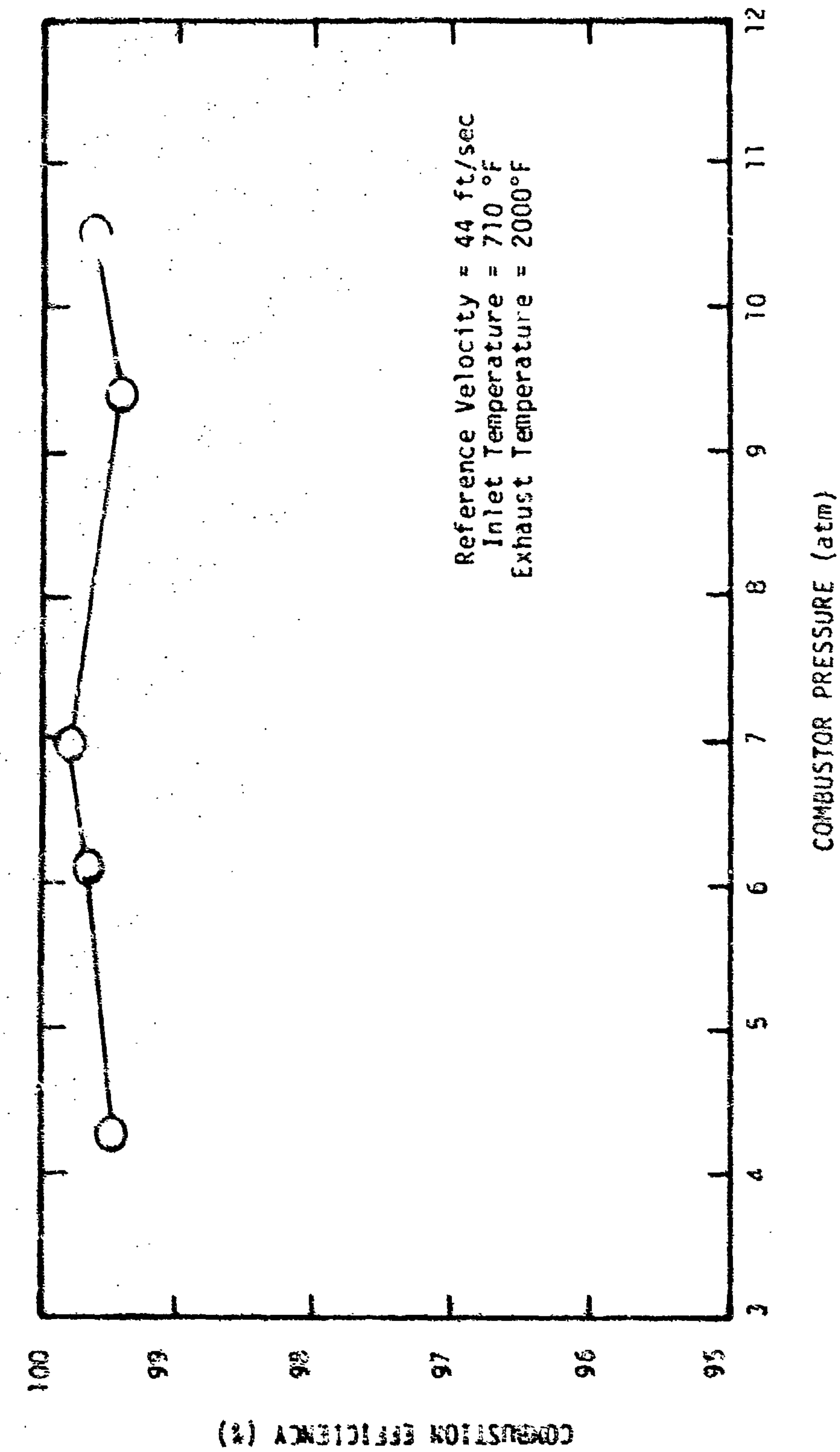

Figure 19. The Effect of Combustor Pressure on Catalytic Combustor Performance

44 feet/sec (13.7 m/sec), and fuel-air ratio was .0212 for these tests (calculated exhaust temperature of 2000°F). No significant pressure effect on combustion efficiency was found -- note that the scale of this curve is one which would emphasize such an effect.

5. OTHER OBSERVATIONS

Velocities of lower than 40 feet/sec (12.5 m/sec) are shown in a cross hatched manner in Figure 18 because it was found that flashback occurred at these conditions. Approximately 15 incidents of flashback were experienced, all during the transitory phase of start-up before coming to steady conditions. At this time personnel were always at the controls and able to quickly shut down fuel flow before damage could occur. It is difficult to say whether this 40 feet/sec observation is in general agreement with other experimental observations of turbulent flame propagation; a brief search did not reveal many studies under similar conditions. Available information is oriented toward turbulent flame propagation behind flameholders and is not directly applicable (References 11, 12).

It should be emphasized that flashback is only one of the problems encountered -- the other was preignition. Ignition of the fuel-air mixture upstream without the necessity of a flame propagation initiated by the catalytic bed is thought to have occurred in the incident that partially damaged the catalytic bed (see Section III.D). These factors contributed to this occurrence:

(1) At the high inlet temperature used for this test (800°F or 700°K), the bed face appeared to be appreciably more active and at a much higher temperature than the tests at lower inlet temperature. Radiation heat transfer caused the upstream flow-distribution plates to increase in temperature to levels in excess of 800°F (700°K).

(2) Flow through the plates caused some stagnation regions which allowed sufficient residence time in contact with the hot stainless steel surface for the fuel-air mixtures to ignite. In the system tested, the onset of preignition caused an increase in the pressure drop across the flow distribution plates. This, in turn, reduced the flow through the rig and a flashback probably occurred at that time.

(3) The possibility of gas-phase ignition, without the effect of the stainless steel plate, should not be dismissed. Ignition delay times at the temperatures of interest (Reference 13) are comparable with the average time between fuel injection and passage through the catalyst bed (10 ms).

Some other observations in the data regarding thermocouple-measured and gas-sample-measured combustion efficiency are worth noting. Disagreements regarding the means of measuring combustion efficiency at idle by those two methods have been cited many times before. It is believed that these disagreements are due to inability to obtain representative samples in both cases. It is further known

that under high temperature conditions (both full power combustor exit conditions and afterburner conditions), direct thermocouple measurements either cannot be made because of thermocouple sheath material limitations or because appreciable corrections must be made to the basic measurement. In this study, fair agreement between gas-sample-measured and thermocouple-measured combustion efficiencies* were attained for exhaust temperatures below 2000°F (1366°K). Above this temperature, the thermocouple-measured efficiency decreased substantially from the gas sample value. (See Figure 20). Although thermocouple radiation correction factors could have been applied to explain some of this diversion, these results again point out the superiority of gas sampling for high temperature combustion efficiency measurement.

* The higher efficiency levels of the thermocouple data at low combustion temperatures may be indicative of the catalytic effect of the platinum/platinum rhodium surfaces.

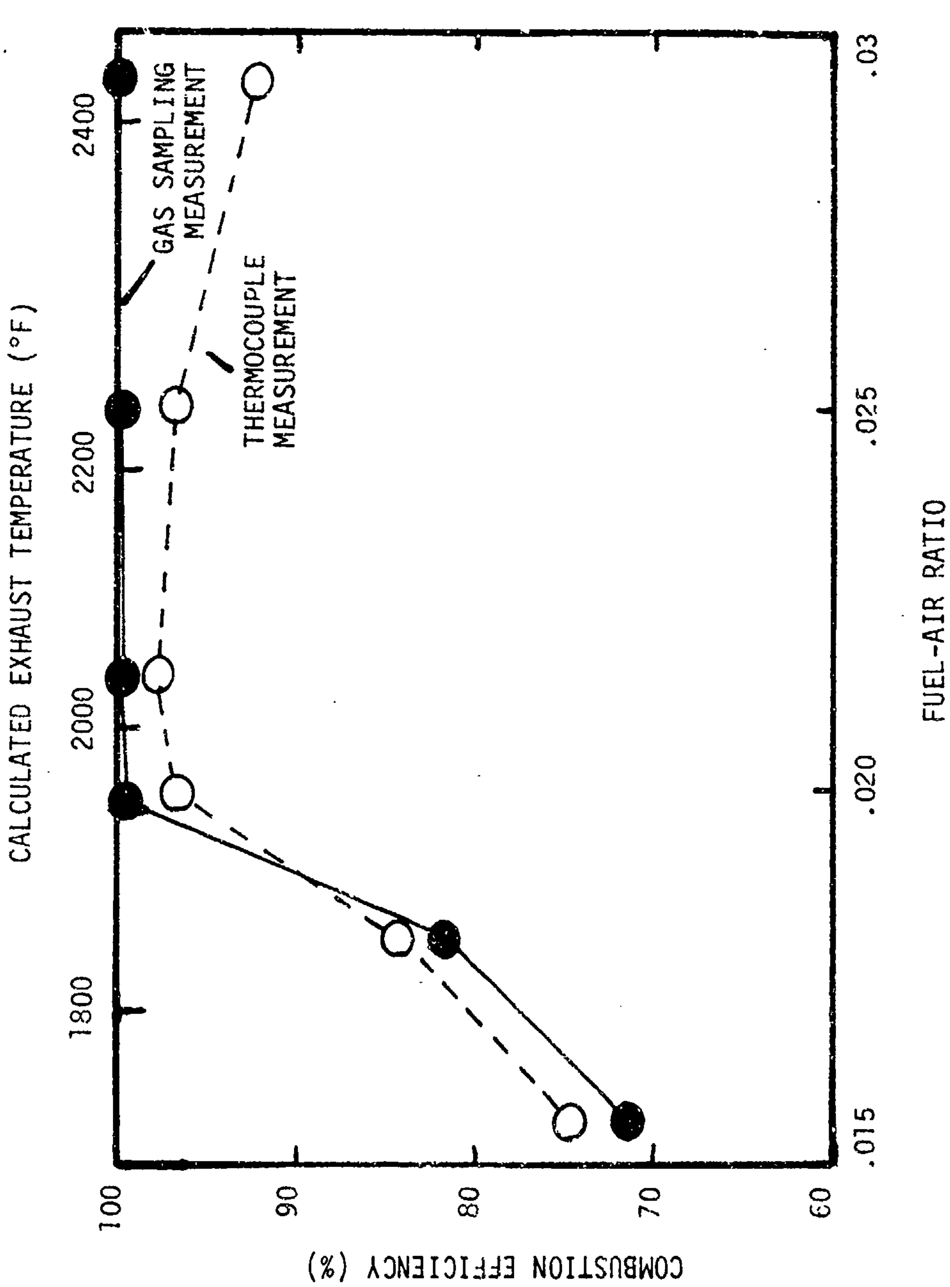

Figure 20. Thermocouple and Gas-Sample Measured Combustion Efficiencies

SECTION V

DISCUSSION

These catalytic combustor results indicate that gas turbine NO_x emissions can be substantially reduced. At the conditions tested, 710°F (648°K) inlet temperature, pressure of 9 atmospheres, exit temperatures of 2000°F (1366°K), a conventional combustor would emit approximately 10gm NO_2/kg fuel. The catalytic combustor NO_x emission was less than 0.1; a decrease by a factor of 100. Should studies indicate stratospheric NO emissions to be cause for concern, this method offers a means of very significant NO reduction.

Results are fairly successful in a number of other ways as well:

a. A specific heat release rate of $3.5 \times 10^6 \frac{\text{BTU}}{\text{atm-hr-ft}^3}$ was achieved with combustion efficiencies of 99.9%. A value of $5 \times 10^6 \frac{\text{BTU}}{\text{atm-hr-ft}^3}$ was achieved with combustion efficiency at 88.2%. Modern turbine engine combustors have specific heat release rates of $5\text{-}10 \times 10^6 \frac{\text{BTU}}{\text{atm-hr-ft}^3}$. Both of these results involved 700°F (644°K) inlet temperatures; substantially greater values might be expected with higher inlet temperatures.

b. Exhaust temperatures of up to 2400°F (1589°K) were achieved. This is within the range of modern engine technology needs. An increase of the catalytic bed temperature to 2700°F (1755°K) may be necessary to allow for some cooling and bypass while maintaining a 2400°F average exhaust temperature.

c. Pressure drops of about 1% ($^{\Delta P}/P$) were encountered.

It is anticipated that most of the losses across an actual catalytic system would be due to the fuel carburetion system. In fact, the $^{\Delta P}/P$ was low enough that a combustion efficiency/pressure drop or specific heat release rate/pressure drop tradeoff might be considered in future designs.

It is interesting to note the lack of performance dependence on combustor pressure. One would expect that if diffusional processes played an important role in determining chemical reaction rate, efficiency would decrease with increasing pressure. This was not the case for the range of pressures tested.

The most serious deficiencies uncovered during this investigation involved low combustion efficiency at low inlet temperatures or fuel-air ratios, or high reference velocity. These are not presently considered to be serious, as design of the combustor did not consider the lower-power operating point. The extent to which this can be improved is not presently known.

The inefficiencies, calculated from the measured CO and C_xH_y concentrations, seemed to be changing character depending on which of the three parameters was being changed. Ratioing the emission index of C_xH_y to that of CO has shown an interesting trend. At the typical operating point previously defined, this value was about 0.1-0.5. When low T_3 or high reference velocity was the predominant cause of inefficiency, the ratio increased to about two. Operation at low fuel-air ratio caused the ratio to be below 0.001. These

results are shown in Figure 21. This analysis may indicate that different operational regions must be considered in a catalytic combustor intended to operate efficiently at low-power conditions.

Flashback and preignition phenomena must be considered in carburetor design. These problems are not characteristic of the catalytic combustor only, but apply to all proposed combustors which use premixing/prevaporization techniques. In fact, it may be expected that low emissions gas phase burners which would probably require slightly higher fuel-air ratios for stability would have greater problems in this respect. In either case, it will not be possible to estimate the actual reliability loss due to these difficulties until engine demonstration of the new control techniques. The NASA Clean Combustor Program results will prove to be especially interesting in this connection.

The next logical step in the development of an acceptable catalytic combustor is the demonstration of good combustion efficiency at idle. Conditions and a goal for such performance are:

Combustor Pressure	= 3 atm
Inlet Temperature	= 300°F (422°K)
Fuel-Air Ratio	= 0.01
Reference Velocity	= 55 ft/sec (17m/sec)
Combustion Inefficiency	= 0.5%

The 0.5% combustion inefficiency goal is derived from that recently

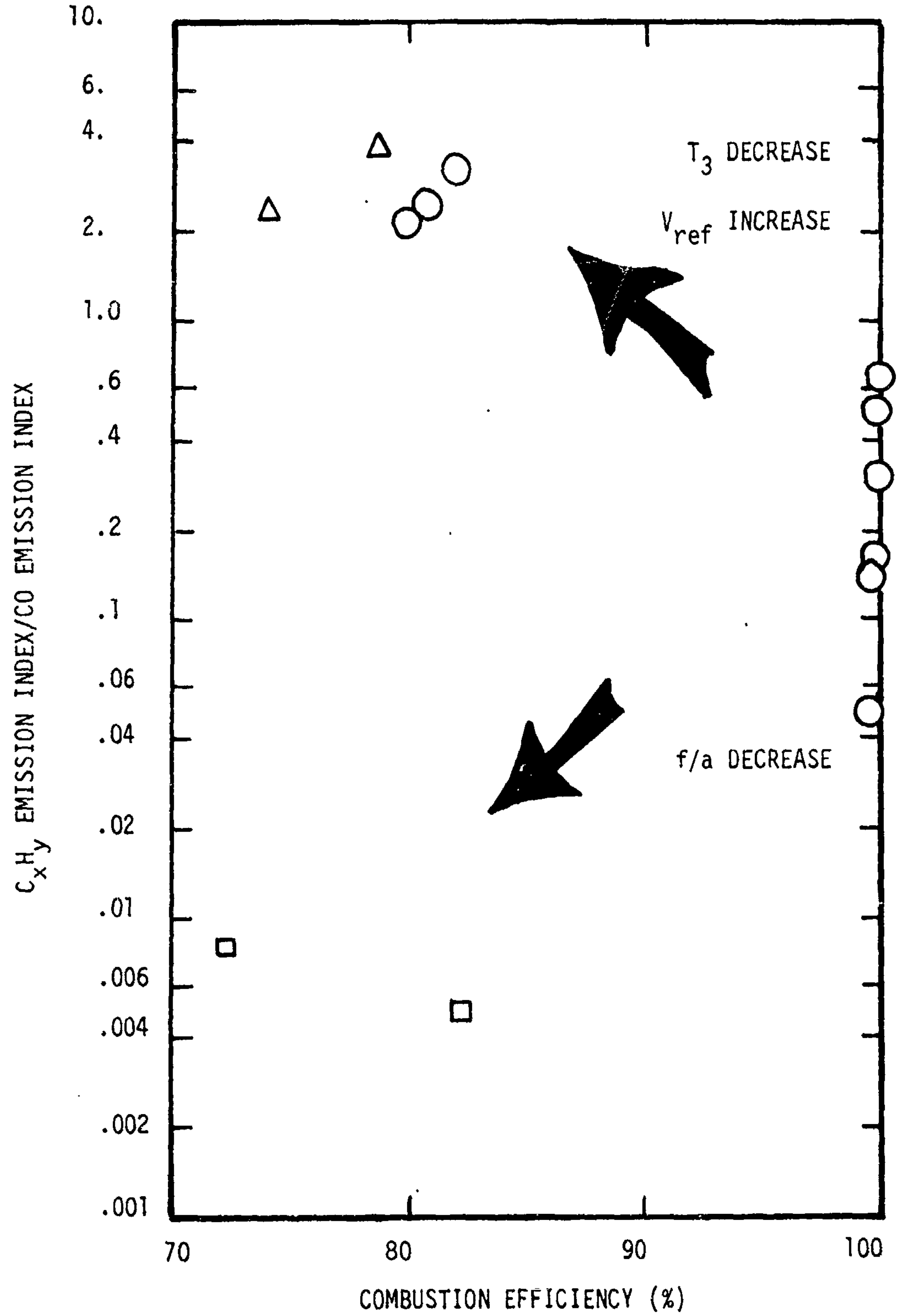

Figure 21. CO/C_xH_y Ratio Variation at Low Combustion Efficiency

specified by EPA (Reference 2) and proposed by AFAPL (Reference 7) for 1983. A program embodying design, construction and test of a catalytic combustor to demonstrate low-power capability is recommended.

Should this program be successful, additional development programs will be necessary to satisfy the additional questions concerning practical fuel system design, reliability and maintainability, starting, and lifetime. Initial efforts in this area would be component rig tests with further development leading to engine demonstration.

Although in the case of aircraft gas turbine emissions the problem of a wide range of operating parameters must be considered, other applications do not place similar demands on the concept. For example, turbines and other combustion devices that run at more or less constant speed (and, hence, combustor inlet conditions) can more easily make use of the development described in this report. In some cases either recirculation or regeneration can be used to raise inlet temperatures to acceptable levels for operation.

SECTION VI

SUMMARY

A catalytic unit was supplied by Engelhard Industries, Menlo Park, New Jersey to AFAPL for testing. Experimental studies at combustor inlet conditions in the following ranges were performed:

Combustor Inlet Temperature	540-710°F (566 - 648°K)
Fuel-Air Ratio	0.015 - 0.029
Exhaust Temperature (Calculated Ideal)	1700-2400°F (1200 - 1589°K)
Combustor Pressure	4 - 10.5 atm
Reference Velocity	44 - 65 ft/sec (13.7-20.3 m/sec)

NO_x emission at all conditions was calculated to yield less than 0.1 gm NO_2/kg fuel (reduced by a factor of 100 from typical conventional combustors). Combustion efficiencies of nearly 100% were attained at the 700°F inlet temperatures (2000°F exhaust temperatures) where specific heat release rates of $3.5 \times 10^6 \frac{\text{BTU}}{\text{atm-hr-ft}^3}$ were achieved. At inlet temperatures below this level severe drops in efficiency were observed. Likewise, lowering fuel-air ratios (or calculated exhaust temperatures) and increasing reference velocity severely reduced combustion efficiency. No effect of combustor pressure on efficiency was found and no reduction in system performance was noted over the 28 hours of testing.

The combustor tested was designed for the high power condition.

Reduced combustion efficiencies at simulated low-power determined during this program are not at all indicative of an optimal design for this condition. Further work to demonstrate the capability to achieve high combustion efficiency at idle operation conditions is recommended. If successful, more involved development programs should be undertaken.

Some problems with premixing and prevaporizing the fuel-air mixture were experienced. Both flashback (propagation of the flame from the catalytic bed face to the carburetor) and preignition (upstream ignition near stagnation regions of the fuel-air mixture flow) are thought to have been experienced.

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